

Global EW fits and the (C)MSSM

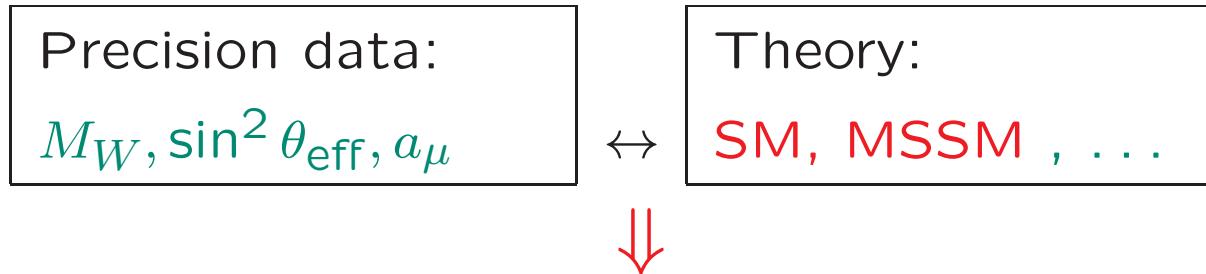
Sven Heinemeyer, IFCA (CSIC, Santander)

BNL, 04/2013

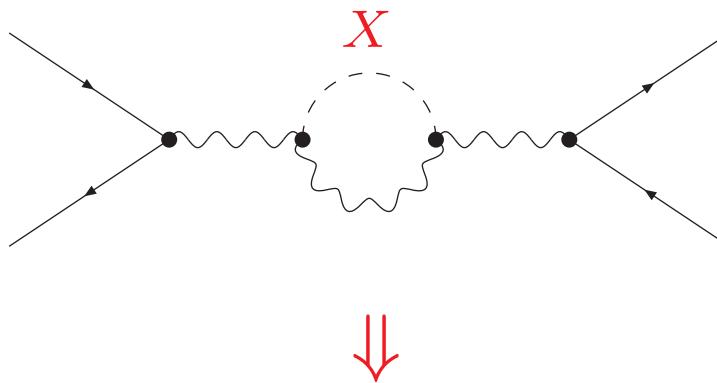
- 1.** Introduction
- 2.** EWPO in the CMSSM
- 3.** EWPO in the MSSM
- 4.** Conclusions

1. Introduction

Comparison of observables with theory:



Test of theory at quantum level: Sensitivity to loop corrections, e.g. X

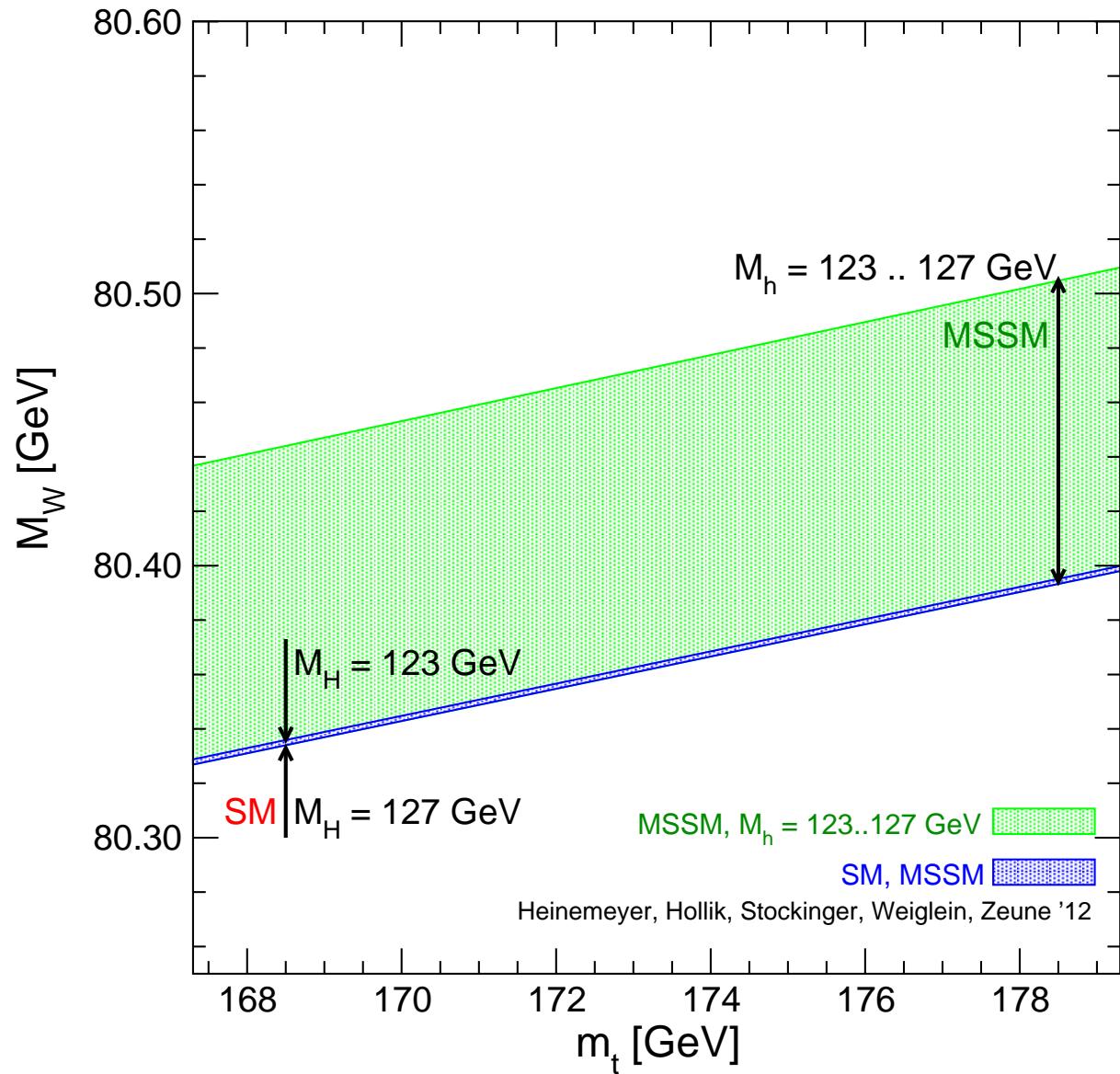


SM: limits on M_X

Very high accuracy of measurements and theoretical predictions needed

Example: Prediction for M_W in the **SM** and the **MSSM** :

[*S.H., W. Hollik, D. Stockinger, G. Weiglein, L. Zeune '12*]



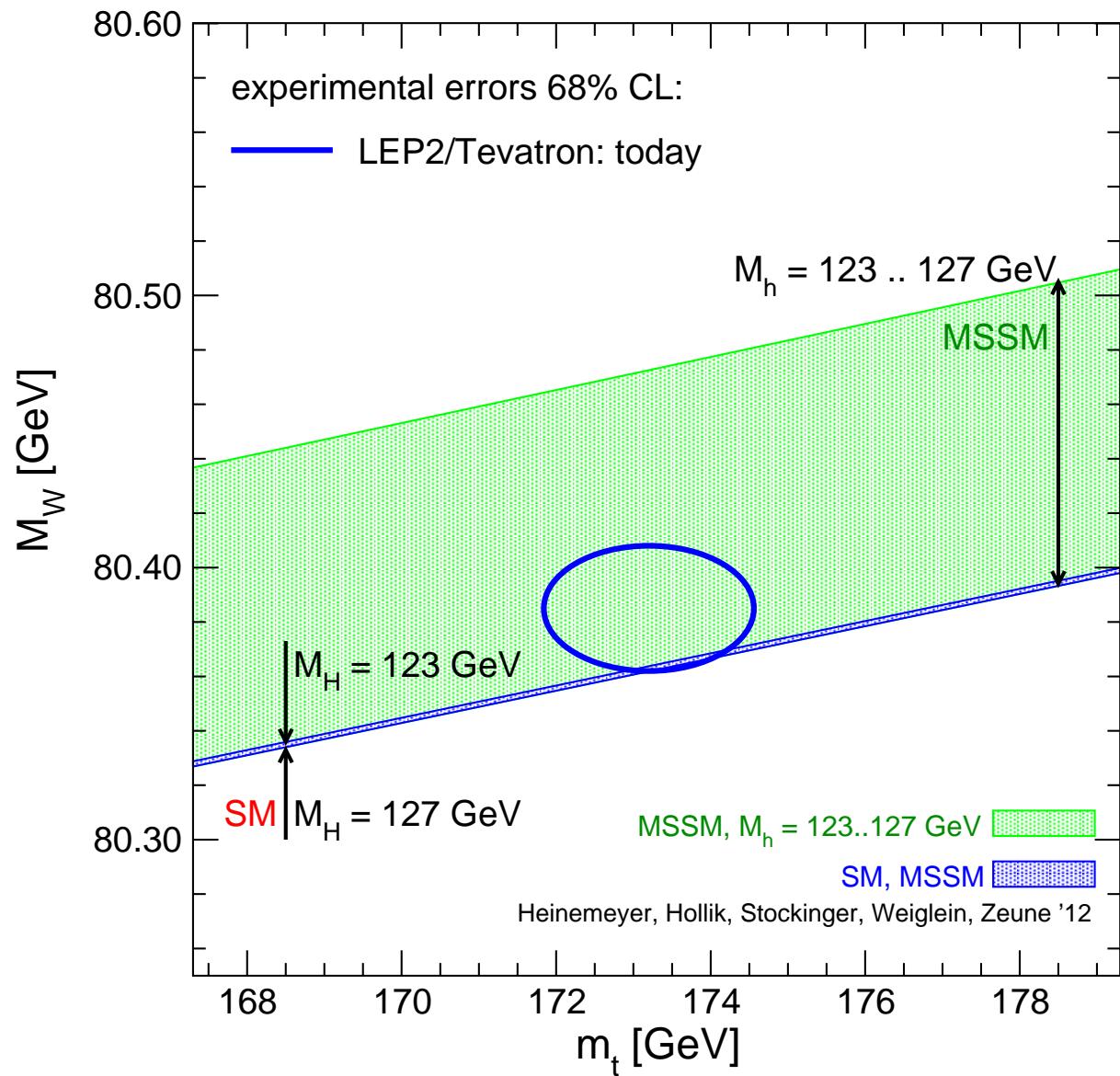
MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of M_H^{SM}

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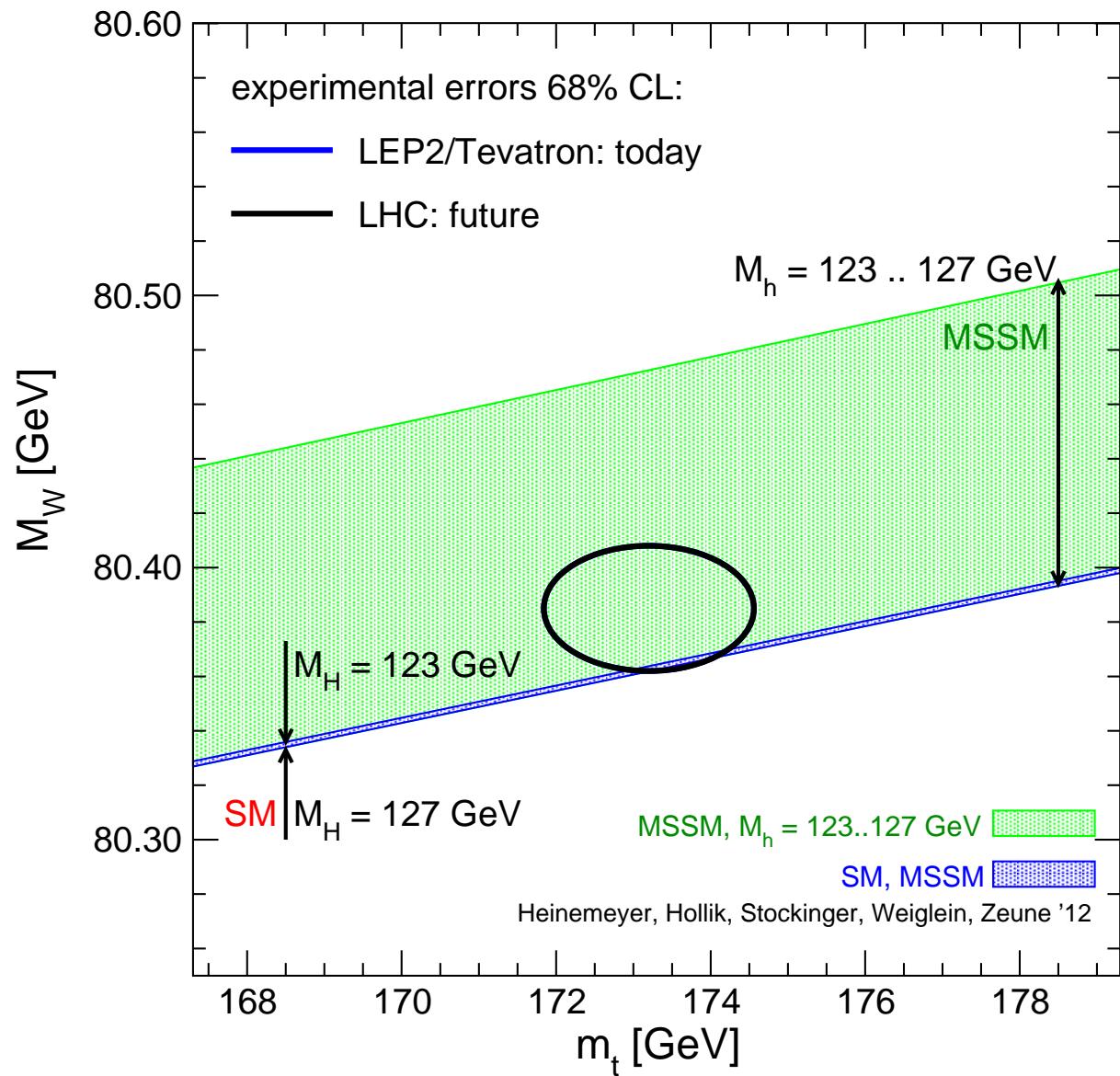
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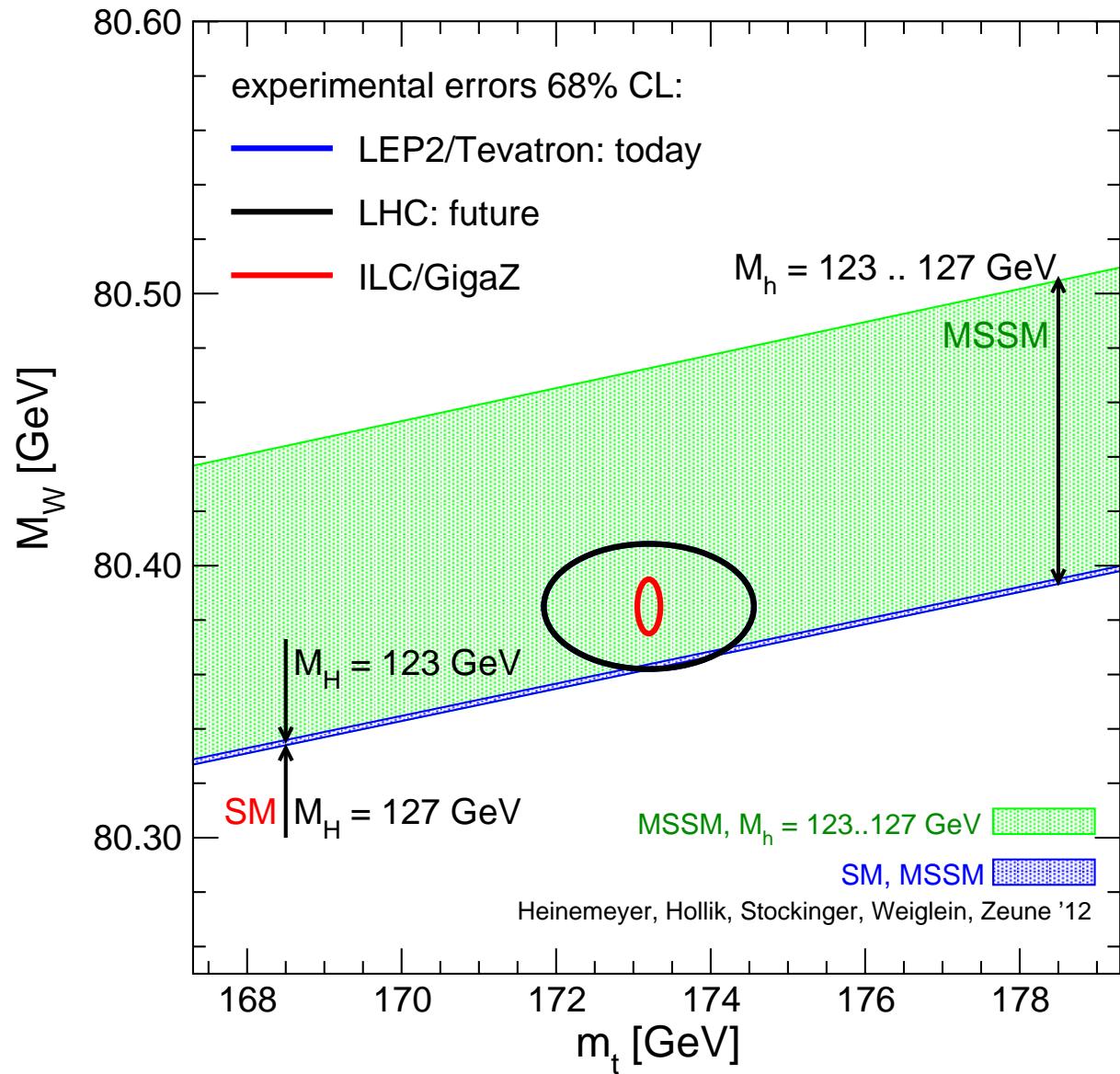
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What about the **ERRORS** ?

Three different types of errors:

Experimental error (\Rightarrow included in the figure):

- current error
- future expectations

\Rightarrow sets the scale, has to be matched by other errors

Theory error:

\Rightarrow error due to missing higher order corrections

- only estimates possible
- even more complicated for the future

Parametric error:

- current uncertainty in the prediction due to error in the input parameters
- future uncertainty

\Rightarrow focus on SM parameters

\Rightarrow derive information about (unknown) SUSY parameters
(SUSY parametric uncertainties highly model dependent)

Precision observables in the SM and the MSSM

M_W , $\sin^2 \theta_{\text{eff}}$, M_h , $(g - 2)_\mu$, b physics, . . .

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_\mu} (1 + \Delta r)$$

\Updownarrow
loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[A. Sirlin '80] , [W. Marciano, A. Sirlin '80]

$$\begin{aligned} \Delta r_{\text{1-loop}} = & \quad \Delta \alpha \quad - \quad \frac{c_W^2}{s_W^2} \Delta \rho \quad + \quad \Delta r_{\text{rem}}(M_H) \\ & \sim \log \frac{M_Z}{m_f} \quad \quad \quad \sim m_t^2 \quad \quad \quad \log(M_H/M_W) \\ & \sim 6\% \quad \quad \quad \sim 3.3\% \quad \quad \quad \sim 1\% \end{aligned}$$

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loop corrections

B) Effective mixing angle:

$$\sin^2 \theta_{\text{eff}} = \frac{1}{4 |Q_f|} \left(1 - \frac{\text{Re } g_V^f}{\text{Re } g_A^f} \right)$$

Higher order contributions:

$$g_V^f \rightarrow g_V^f + \Delta g_V^f, \quad g_A^f \rightarrow g_A^f + \Delta g_A^f$$

Corrections to M_W , $\sin^2 \theta_{\text{eff}}$ → approximation via the ρ -parameter:

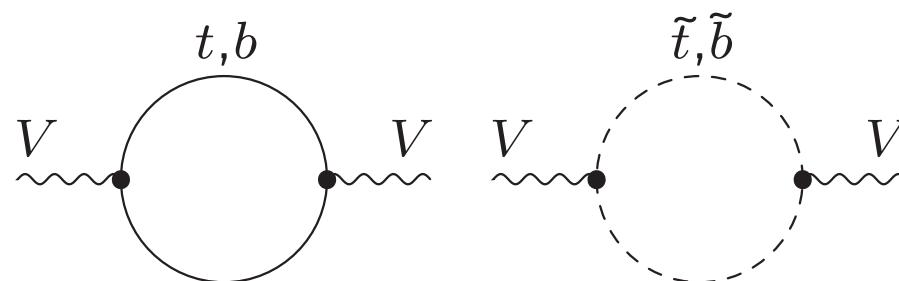
ρ measures the relative strength between
neutral current interaction and charged current interaction

$$\rho = \frac{1}{1 - \Delta\rho} \quad \Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}$$

(leading, process independent terms)

$\Delta\rho$ gives the main contribution to EW observables:

$$\Delta M_W \approx \frac{M_W}{2} \frac{c_W^2}{c_W^2 - s_W^2} \Delta\rho, \quad \Delta \sin^2 \theta_W^{\text{eff}} \approx - \frac{c_W^2 s_W^2}{c_W^2 - s_W^2} \Delta\rho$$



$\Delta\rho^{\text{SUSY}}$ from \tilde{t}/\tilde{b} loops $> 0 \Rightarrow M_W^{\text{SUSY}} \gtrsim M_W^{\text{SM}}$

Experimental errors of the precision observables:

	today	Tev./LHC	LC	GigaZ
$\delta \sin^2 \theta_{\text{eff}} (\times 10^5)$	16	16	—	1.3
δM_W [MeV]	15	≤ 15	10	7
δm_t [GeV]	0.9	≤ 1	0.2	0.1

Relevant SM parametric errors: $\delta(\Delta\alpha_{\text{had}}) = 5 \times 10^{-5}$, $\delta M_Z = 2.1$ MeV

	$\delta m_t = 2$	$\delta m_t = 1$	$\delta m_t = 0.1$	$\delta(\Delta\alpha_{\text{had}})$	δM_Z
$\delta \sin^2 \theta_{\text{eff}} [10^{-5}]$	6	3	0.3	1.8	1.4
ΔM_W [MeV]	12	6	1	1	2.5

Current and future errors:

<u>Current:</u>	$\delta m_t^{\text{exp}} = 0.9 \text{ GeV},$	$\delta(\Delta\alpha_{\text{had}}) = 3.5 \times 10^{-4}$
	$\text{SM : } \delta M_W^{\text{theory}} \approx \pm 4 \text{ MeV},$	$\delta \sin^2 \theta_{\text{eff}}^{\text{theory}} \approx \pm 4.7 \times 10^{-5}$
	$\text{MSSM : } \delta M_W^{\text{theory}} \approx \pm(5 - 10) \text{ MeV},$	$\delta \sin^2 \theta_{\text{eff}}^{\text{theory}} \approx \pm(5 - 7) \times 10^{-5}$
$\delta m_t :$	$\delta M_W^{\text{para}} \approx \pm 5.5 \text{ MeV},$	$\delta \sin^2 \theta_{\text{eff}}^{\text{para}} \approx \pm 7 \times 10^{-5}$
$\delta(\Delta\alpha_{\text{had}}) :$	$\delta M_W^{\text{para}} \approx \pm 6.5 \text{ MeV},$	$\delta \sin^2 \theta_{\text{eff}}^{\text{para}} \approx \pm 13 \times 10^{-5}$
	$\delta M_W^{\text{exp}} \approx \pm 15 \text{ MeV},$	$\delta \sin^2 \theta_{\text{eff}}^{\text{exp}} \approx \pm 16 \times 10^{-5}$
<u>Future:</u>		
	$\text{SM : } \delta M_W^{\text{theory}} \gtrsim \pm 2 \text{ MeV},$	$\delta \sin^2 \theta_{\text{eff}}^{\text{theory}} \gtrsim \pm 2 \times 10^{-5}$
	$\text{MSSM : } \delta M_W^{\text{theory}} \gtrsim \pm (3 - 5) \text{ MeV},$	$\delta \sin^2 \theta_{\text{eff}}^{\text{theory}} \gtrsim \pm (2.5 - 3.5) \times 10^{-5}$
$\delta m_t :$	$\delta M_W^{\text{para}} \approx \pm 1 \text{ MeV},$	$\delta \sin^2 \theta_{\text{eff}}^{\text{para}} \approx \pm 0.4 \times 10^{-5}$
$\delta(\Delta\alpha_{\text{had}}) :$	$\delta M_W^{\text{para}} \approx \pm 1 \text{ MeV},$	$\delta \sin^2 \theta_{\text{eff}}^{\text{para}} \approx \pm 1.8 \times 10^{-5}$
[GigaZ] :	$\delta M_W^{\text{exp}} \approx \pm 7 \text{ MeV},$	$\delta \sin^2 \theta_{\text{eff}}^{\text{exp}} \approx \pm 1.3 \times 10^{-5}$

Indirect determination of M_H^{SM} :

[LEPEEWG '12]

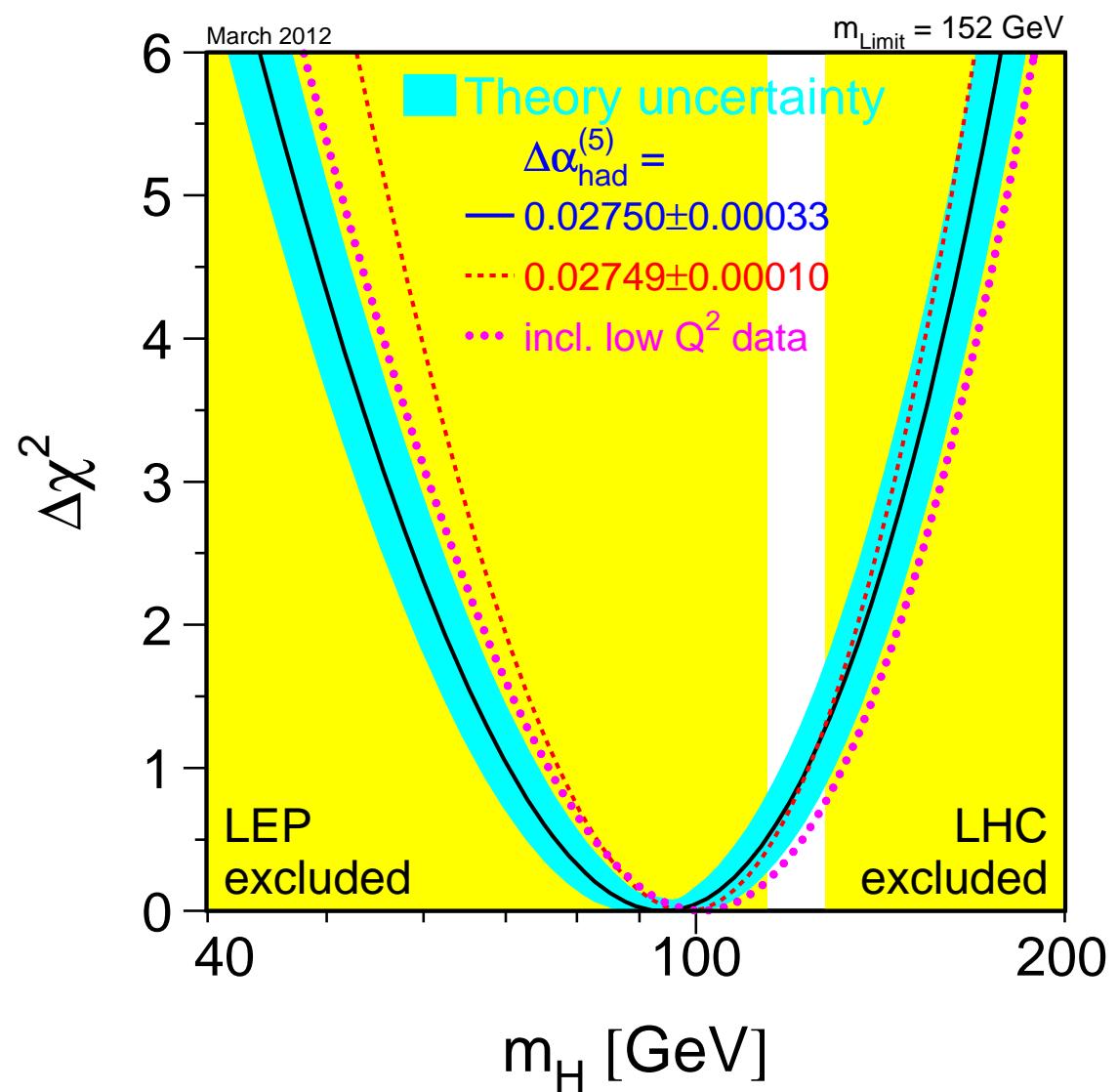
$$\Rightarrow M_H = 94^{+29}_{-24} \text{ GeV}$$

$M_H < 152 \text{ GeV}, 95\% \text{ C.L.}$

Assumption for the fit:

SM incl. Higgs boson

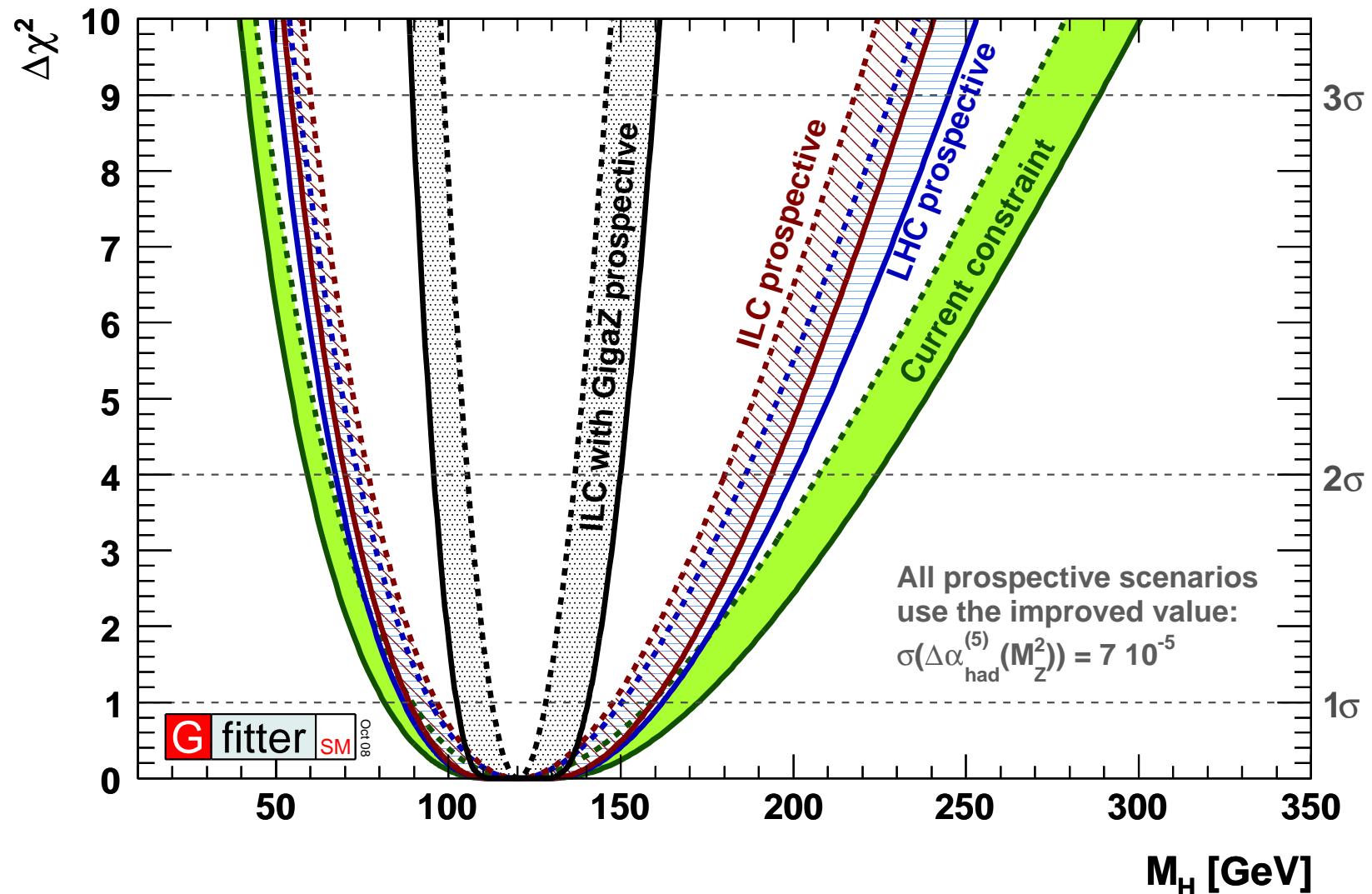
\Rightarrow no confirmation of
Higgs mechanism



\Rightarrow Higgs boson seems to be light, $M_H \lesssim 160 \text{ GeV}$

Improvement in the Blue Band plot:

[*GFitter '09*]



(note: artificially $M_H^{\text{SM}} = 120$ GeV)

2. EWPO in the CMSSM

⇒ see back-up for definitions

- Electroweak precision observables (**EWPO**) ?
- B physics observables (**BPO**) ?
- Cold dark matter (**CDM**) ?

⇒ combination of EWPO, BPO, CDM ?

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EWPO M_W : information on $m_{\tilde{t}}$, $m_{\tilde{b}}$ or M_A , $\tan \beta$ or ...

EWPO $(g - 2)_\mu$: information on $\tan \beta$ and/or $m_{\tilde{\chi}^0}$, $m_{\tilde{\chi}^\pm}$ and/or $m_{\tilde{\mu}}$, $m_{\tilde{\nu}_\mu}$

BPO $\text{BR}(b \rightarrow s\gamma)$: information on $\tan \beta$ and/or M_{H^\pm} and/or $m_{\tilde{t}}$, $m_{\tilde{\chi}^\pm}$

CDM (LSP gives CDM) : information on $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}}$ or M_A or ...

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CDM (LSP gives CDM) : information on $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}}$ or M_A or ...

⇒ combination makes only sense if all parameters are connected!

⇒ GUT based models: CMSSM, NUHM1, ...

Testing SUSY with m_t and M_W

Sensitive test of any model:

Fit m_t and/or M_W and compare with experimental values:

$$m_t^{\text{exp}} = 173.1 \pm 1.3 \text{ GeV}$$

$$M_W^{\text{exp}} = 80.399 \pm 0.023 \text{ GeV}$$

[LEPEWWG '09]

[TevEWWG '09]

$$m_t^{\text{fit,SM,excl. } M_W} = 172.6_{-10.2}^{+13.3} \text{ GeV}$$

$$m_t^{\text{fit,SM,incl. } M_W} = 179.3_{-8.5}^{+11.6} \text{ GeV}$$

$$M_W^{\text{fit,SM,excl. } m_t} = 80.363 \pm 0.032 \text{ GeV}$$

$$M_W^{\text{fit,SM,incl. } m_t} = 80.364 \pm 0.020 \text{ GeV}$$

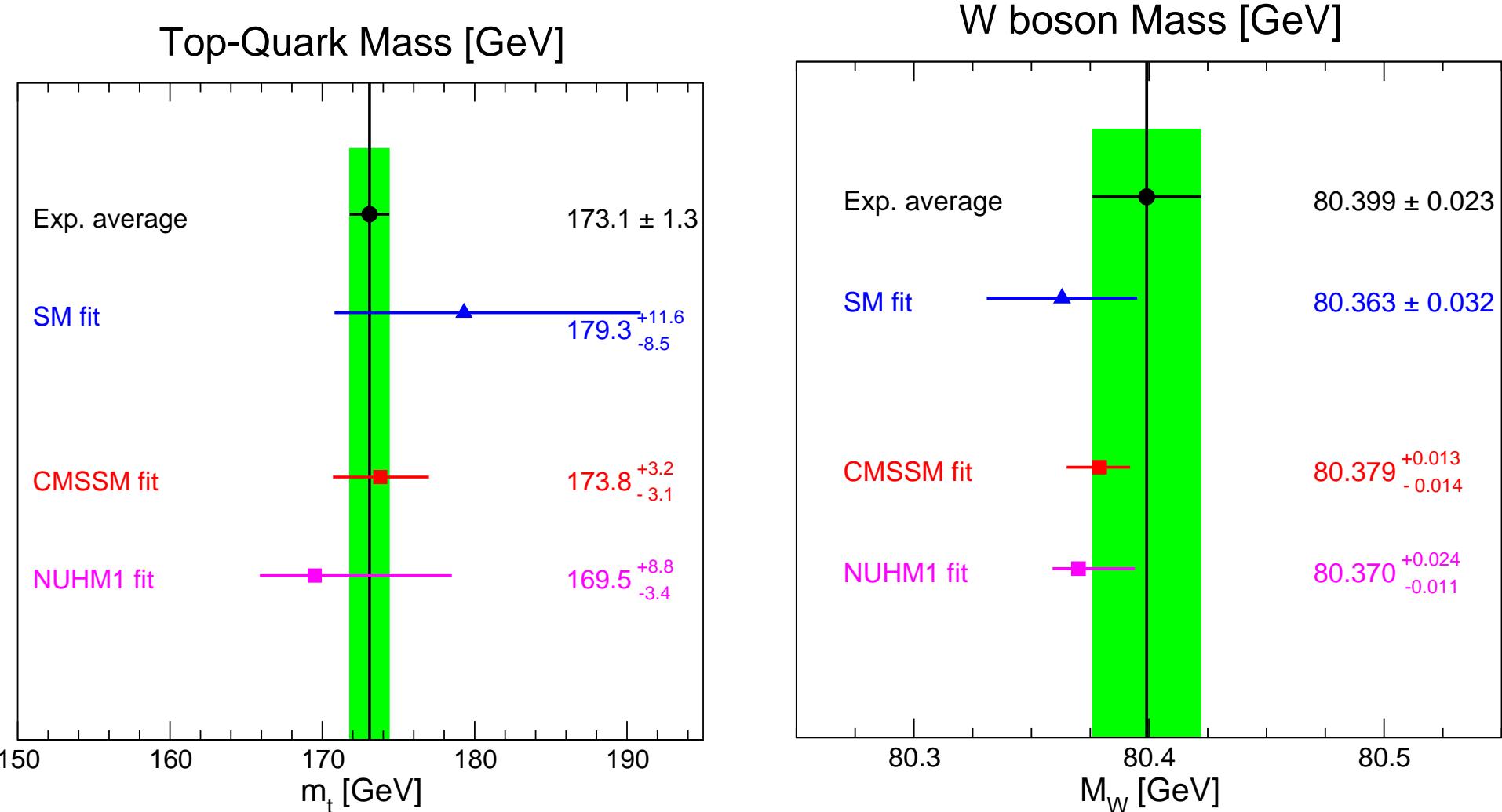
⇒ non-trivial success of the SM

⇒ quantum corrections up to two-loop needed

M_W fit: M_W not included, m_t fit: m_t not included

(SM fit: M_H not included – CMSSM/NUHM1 fit: M_h included)

[2009]



⇒ CMSSM and NUHM1 fit amazingly well m_t and M_W

⇒ better than the SM: smaller errors, better best-fit points

3. EWPO in the MSSM

Questions:

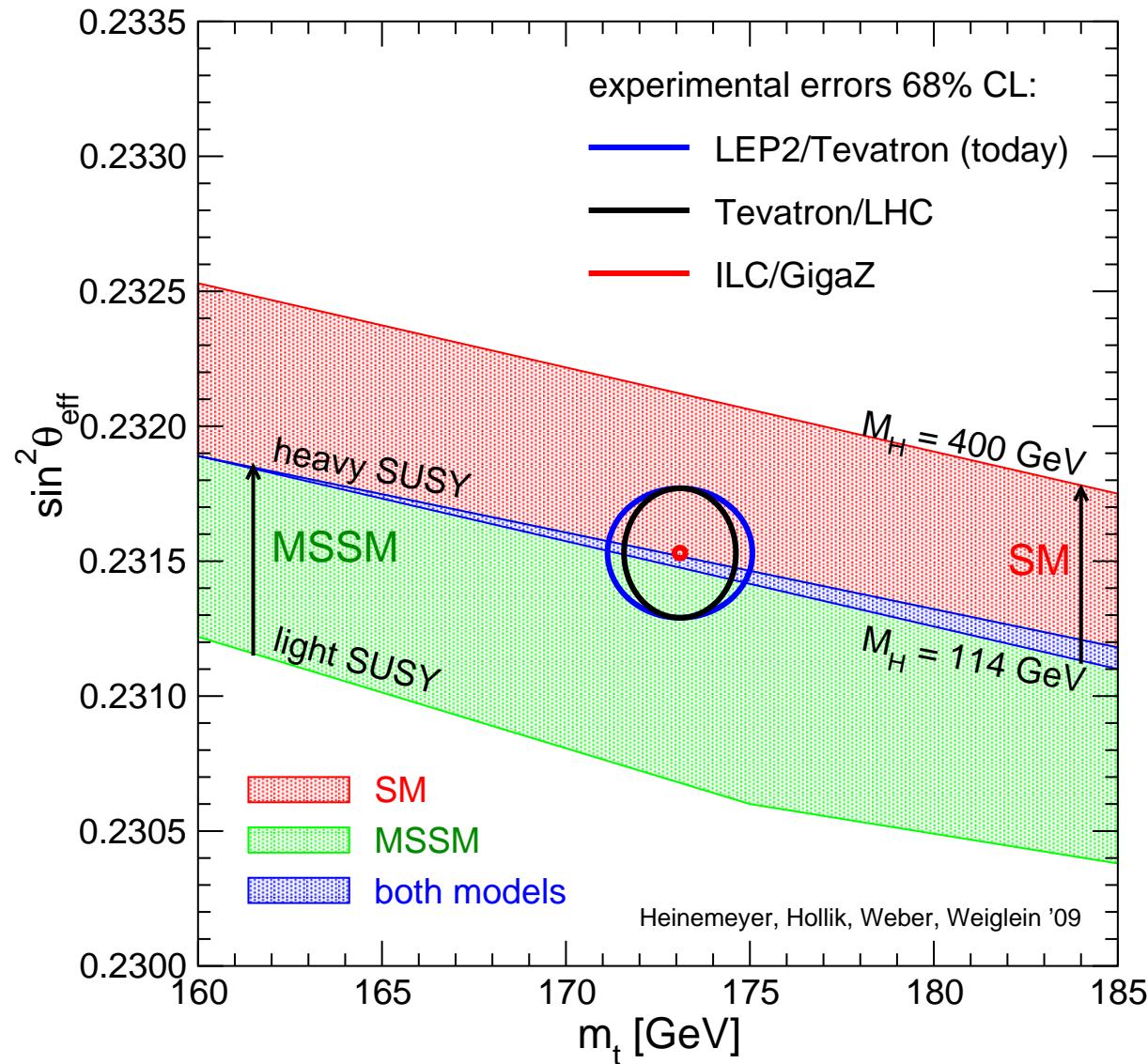
1. Can one model be favored over the other now?
2. Can one model be favored over the other with LC/GigaZ precision?
3. Can certain MSSM parameters be favored by the EWPO?

⇒ focus on M_W and $\sin^2 \theta_{\text{eff}}$

⇒ most precise and best calculated EWPO in the MSSM

Prediction for $\sin^2 \theta_{\text{eff}}$ in the SM and the MSSM :

[S.H., W. Hollik, A. Weber, G. Weiglein '07]



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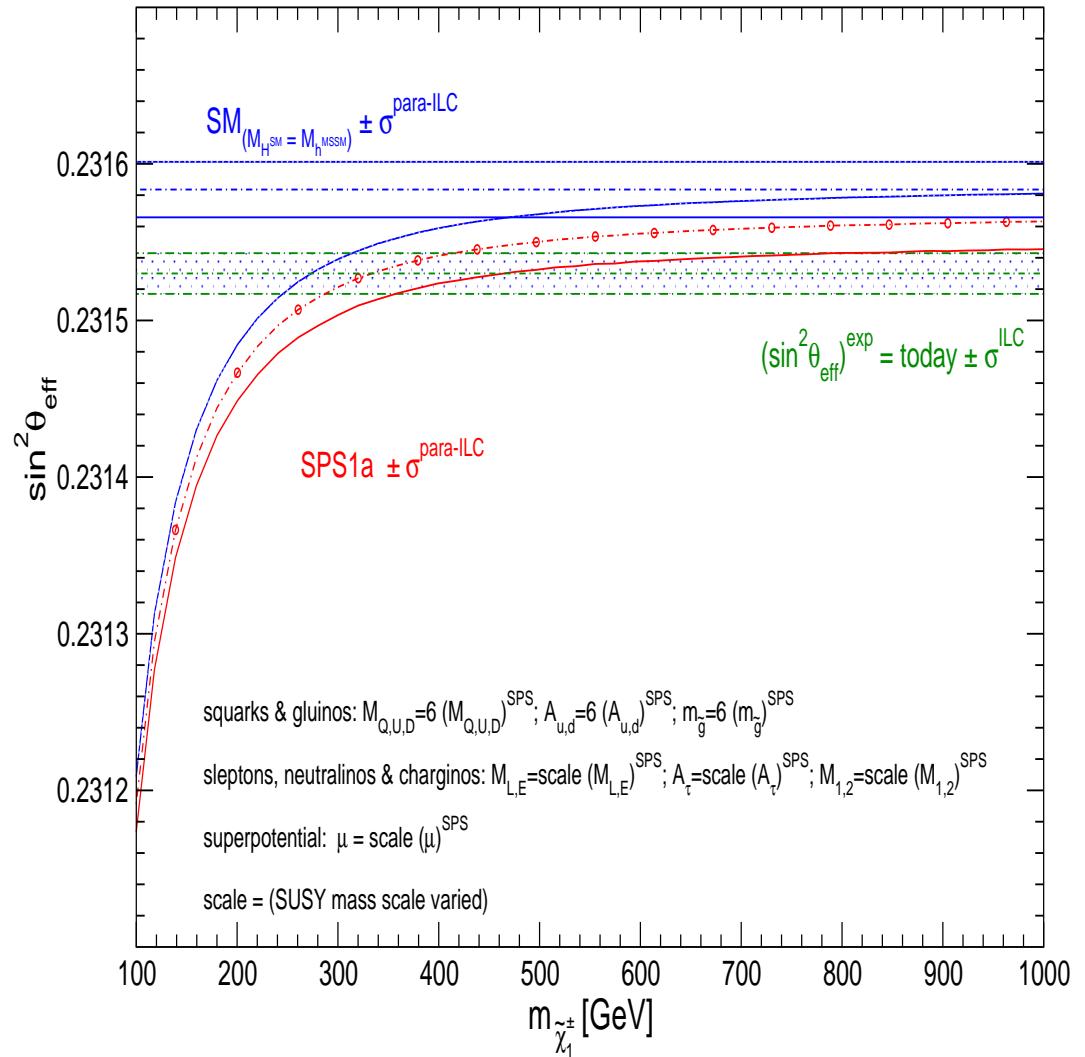
Scenario with no SUSY particles at the LHC:

- $\sin^2 \theta_{\text{eff}}$ investigation
- SPS 1a with heavy scalars

SM prediction
vs.

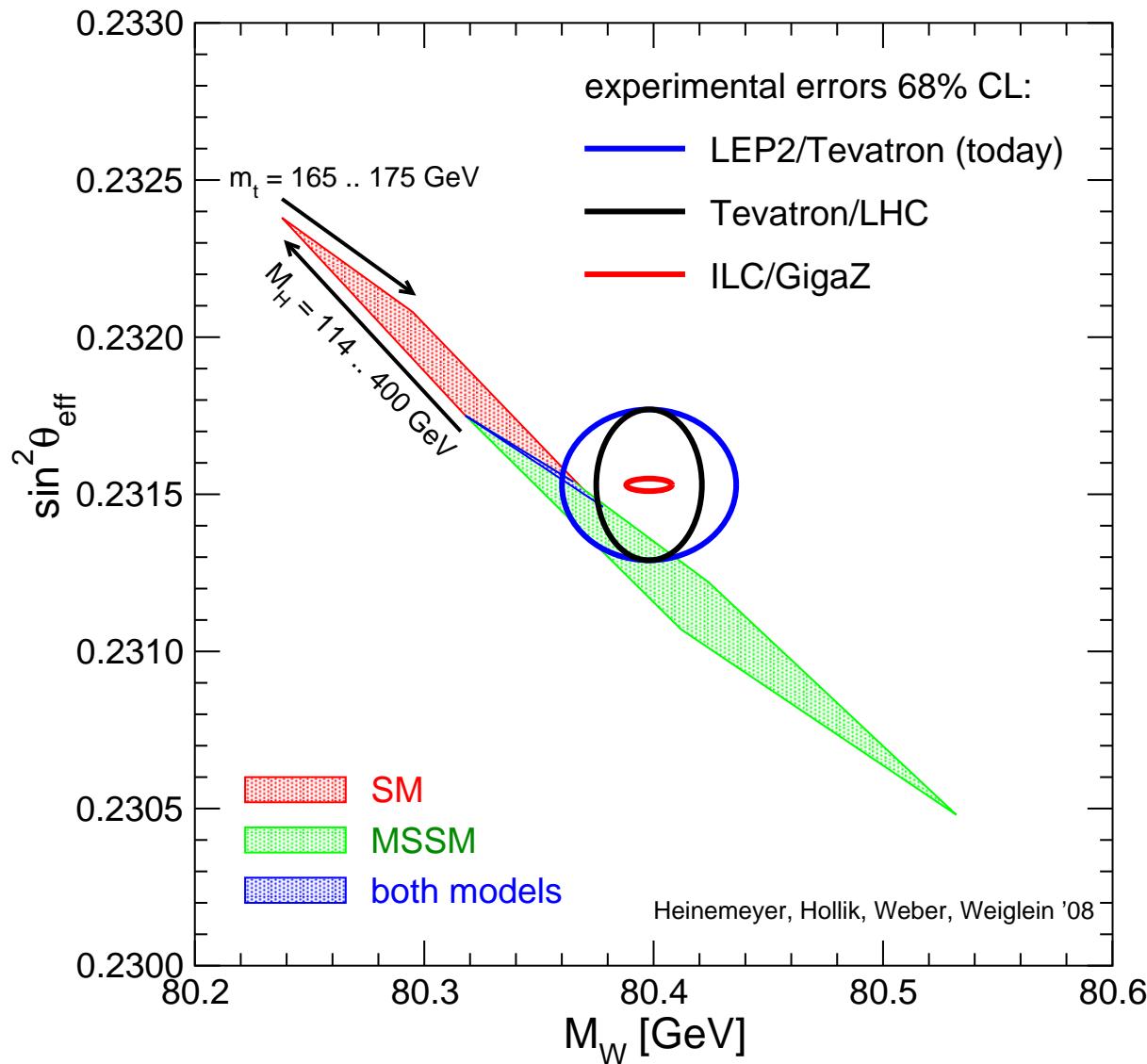
MSSM (SPS 1a) prediction
vs.

LC resolution



- the LC(1000)/GigaZ could detect SUSY directly/indirectly

Example: Prediction for M_W and $\sin^2 \theta_{\text{eff}}$ in the **SM** and the **MSSM** :
[S.H., W. Hollik, A. Weber, G. Weiglein '10]

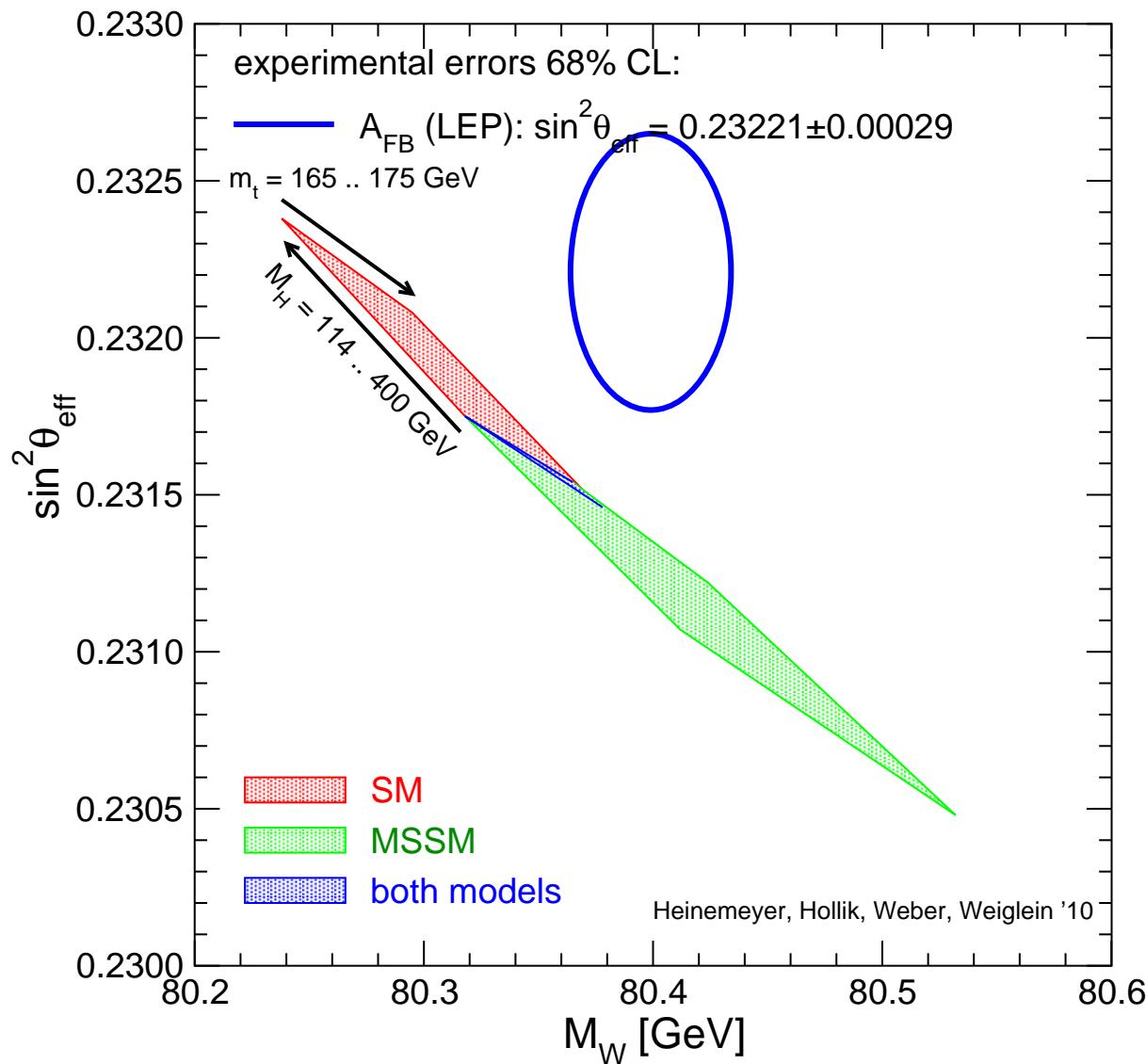


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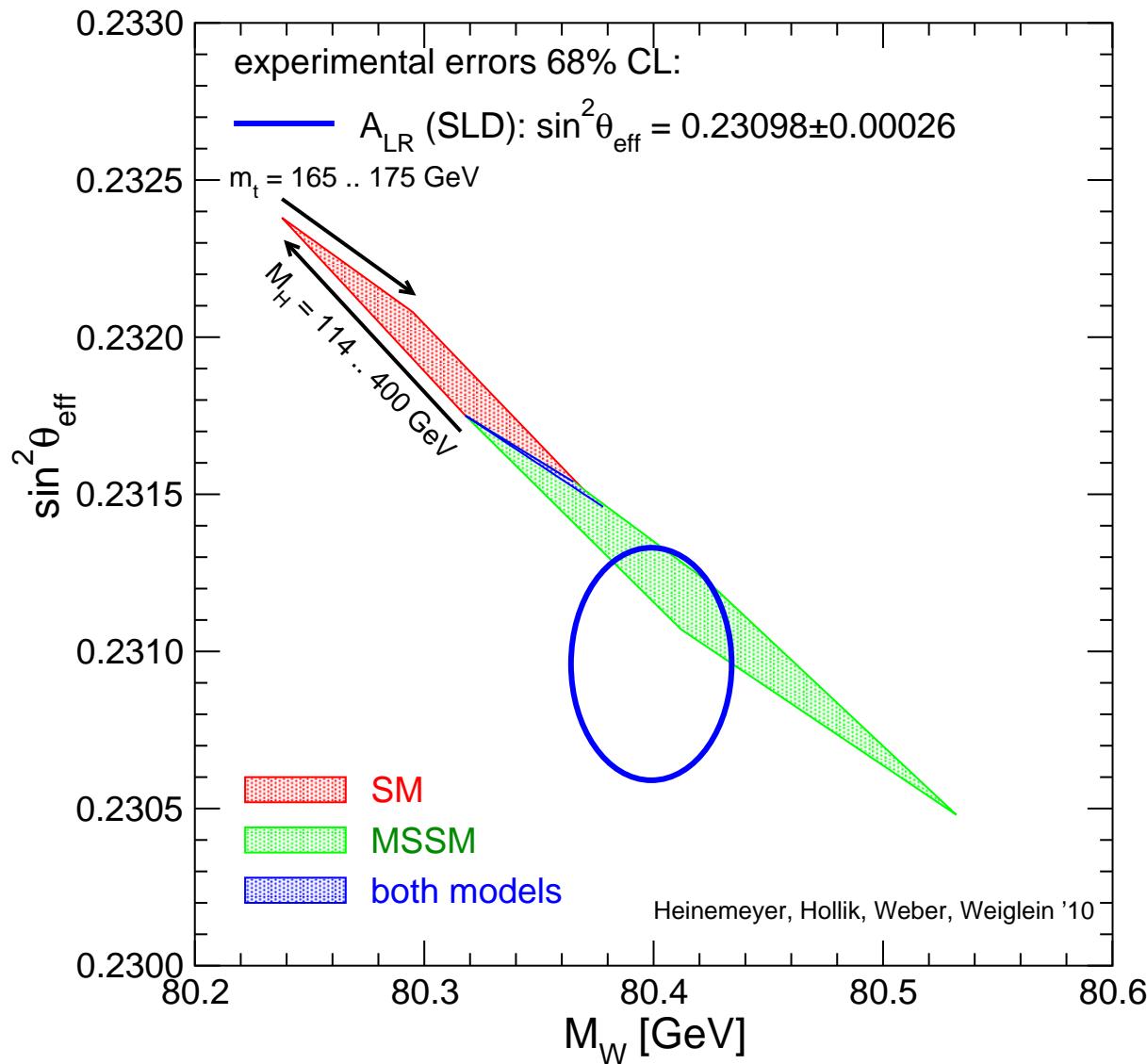
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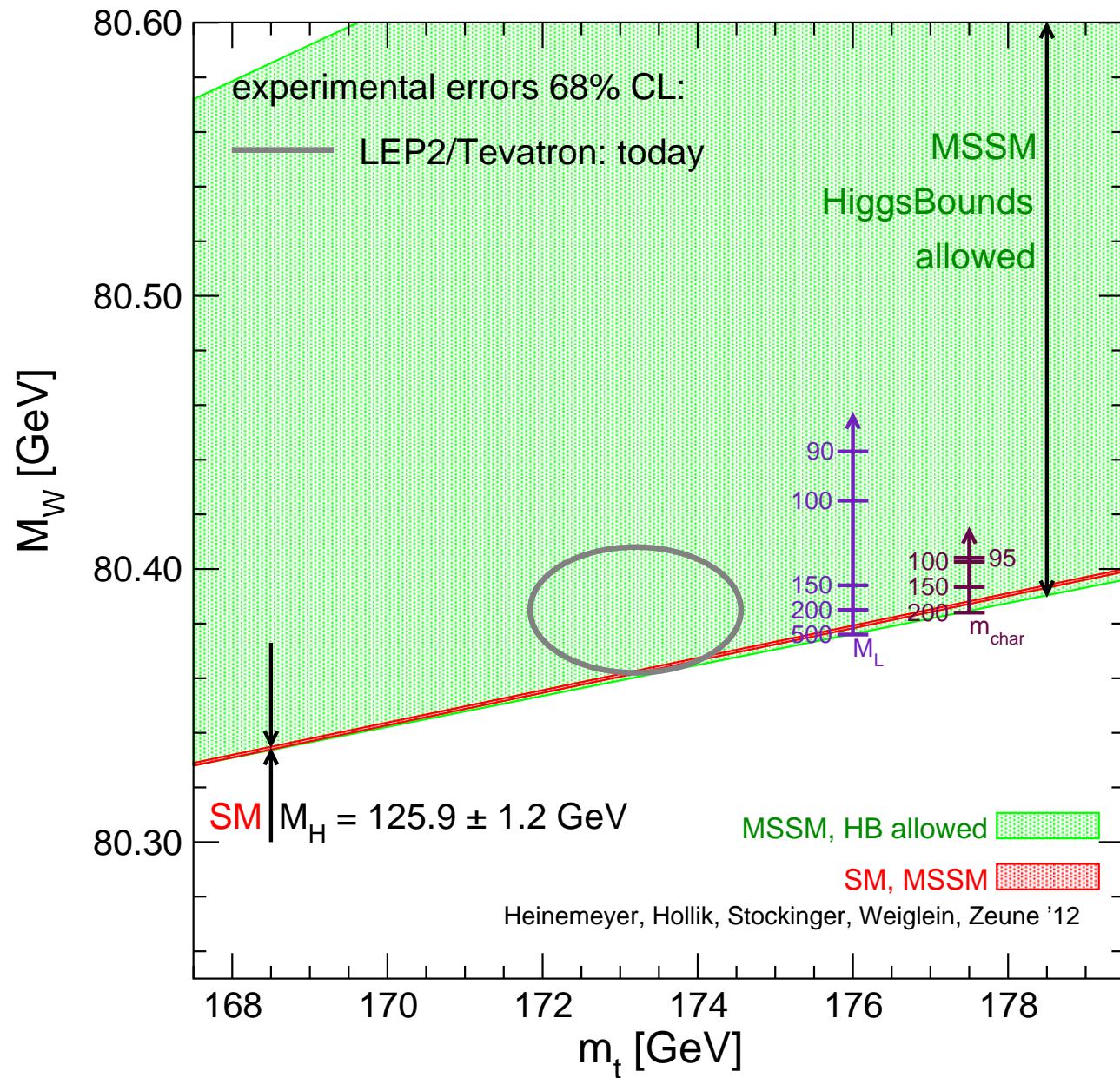
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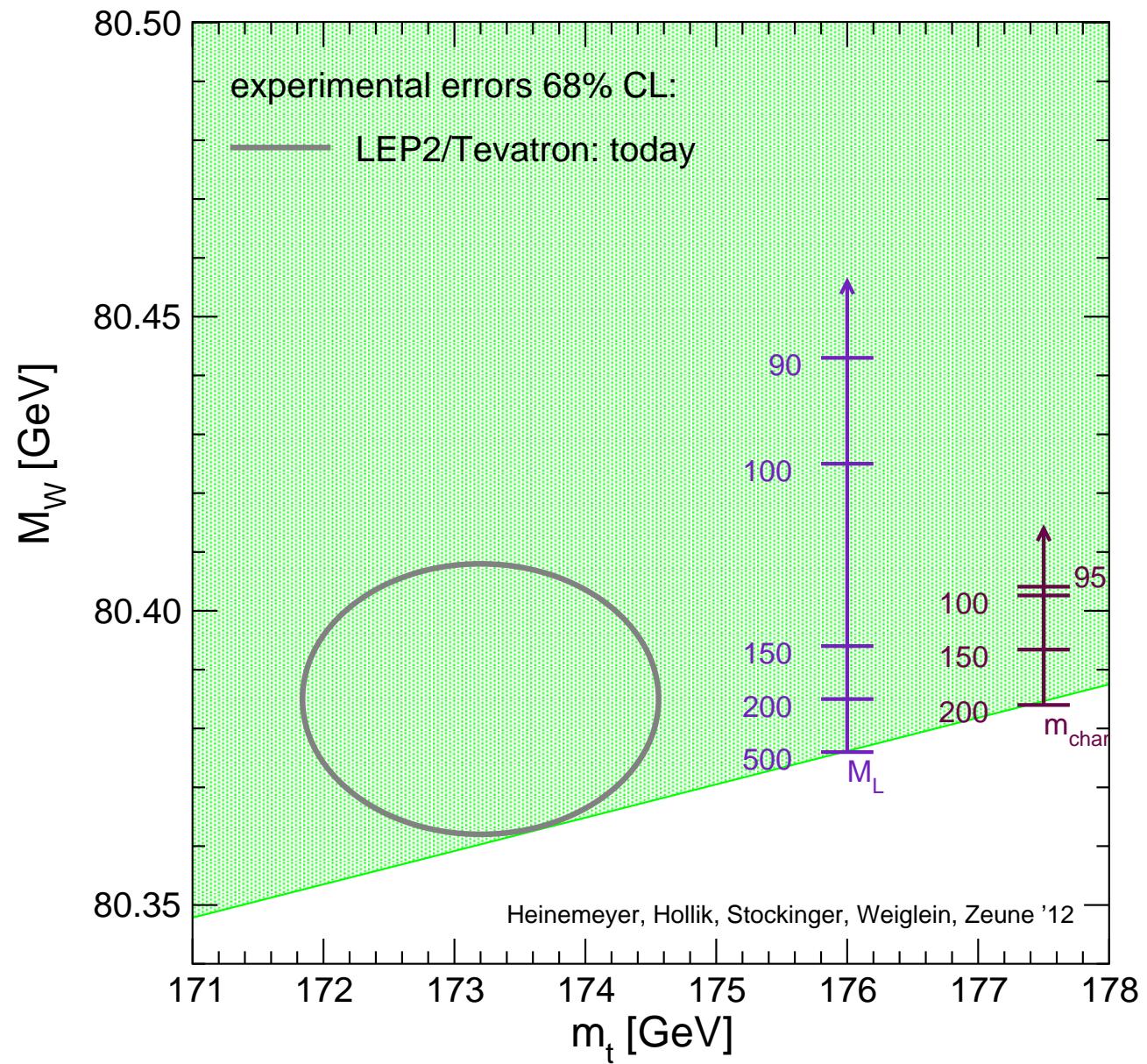
⇒ extensive parameter scan:

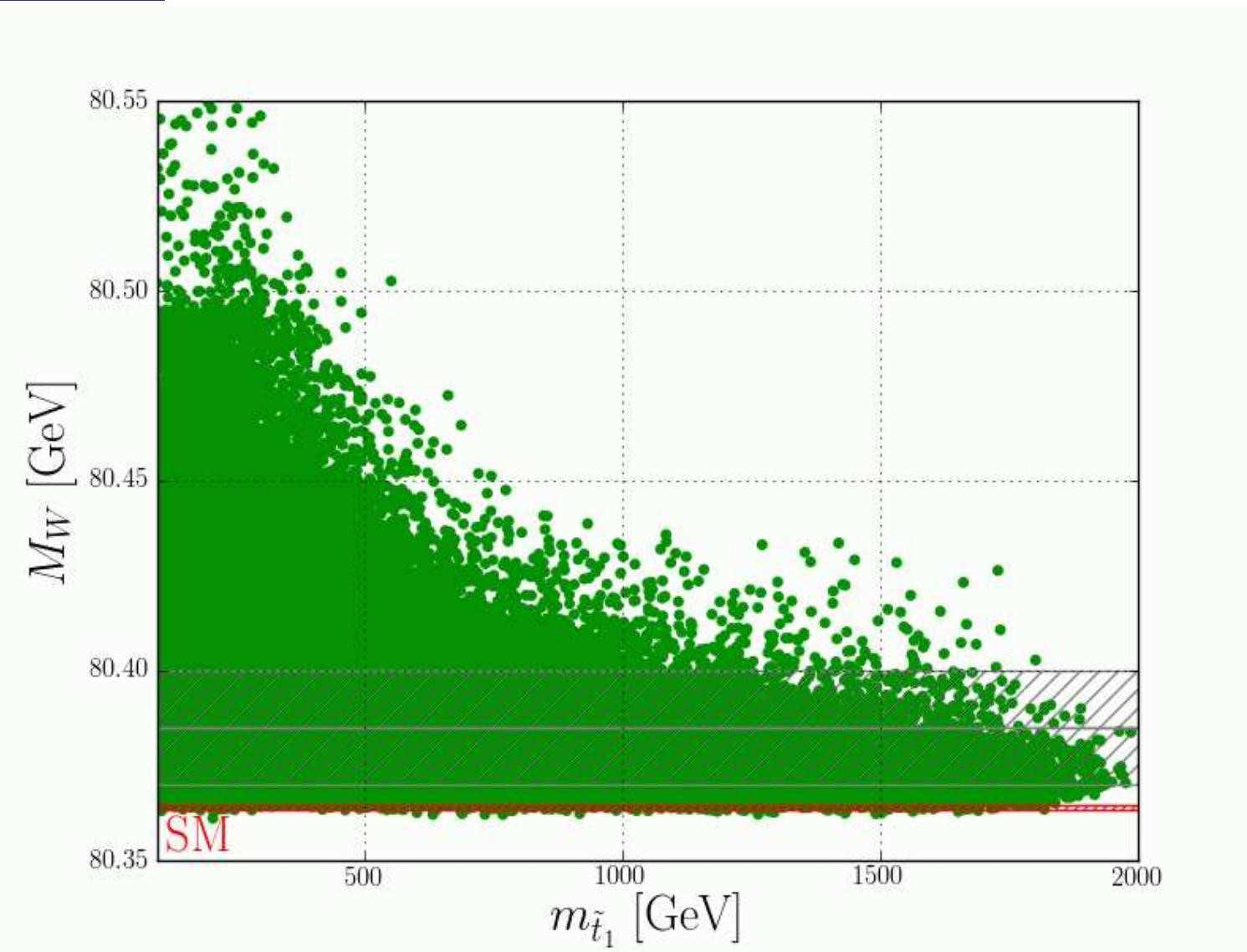
Parameter	Minimum	Maximum
μ	-2000	2000
$M_{\tilde{E}_{1,2,3}} = M_{\tilde{L}_{1,2,3}}$	100	2000
$M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}}$	500	2000
$M_{\tilde{Q}_3}$	100	2000
$M_{\tilde{U}_3}$	100	2000
$M_{\tilde{D}_3}$	100	2000
$A_e = A_\mu = A_\tau$	$-3 M_{\tilde{E}}$	$3 M_{\tilde{E}}$
$A_u = A_d = A_c = A_s$	$-3 M_{\tilde{Q}_{12}}$	$3 M_{\tilde{Q}_{12}}$
A_b	$-3 \max(M_{\tilde{Q}_3}, M_{\tilde{D}_3})$	$3 \max(M_{\tilde{Q}_3}, M_{\tilde{D}_3})$
A_t	$-3 \max(M_{\tilde{Q}_3}, M_{\tilde{U}_3})$	$3 \max(M_{\tilde{Q}_3}, M_{\tilde{U}_3})$
$\tan \beta$	1	60
M_3	500	2000
M_A	90	1000
M_2	100	1000

Effects of charginos and staus: [S.H., G. Weiglein, L. Zeune '12 - PRELIMINARY]

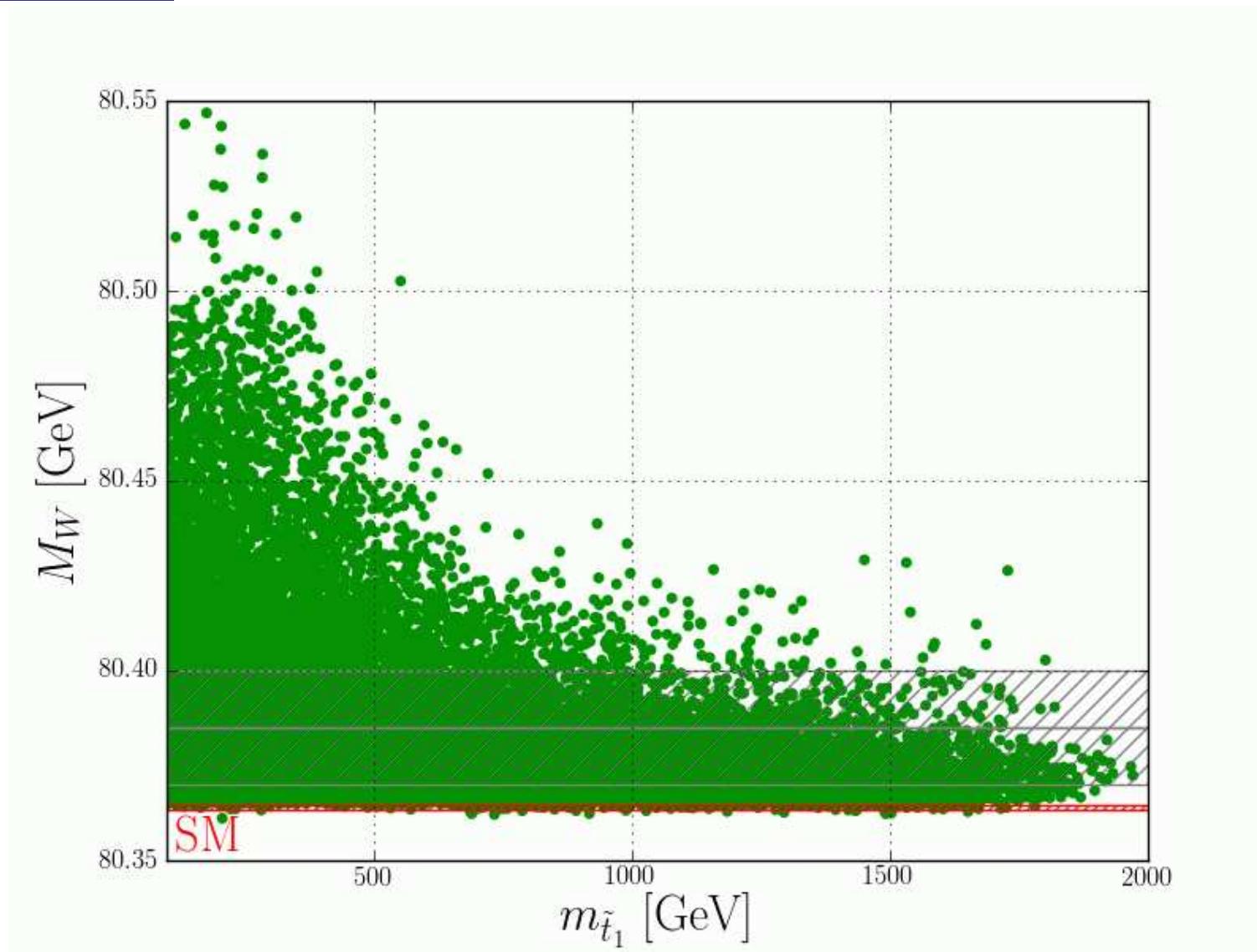


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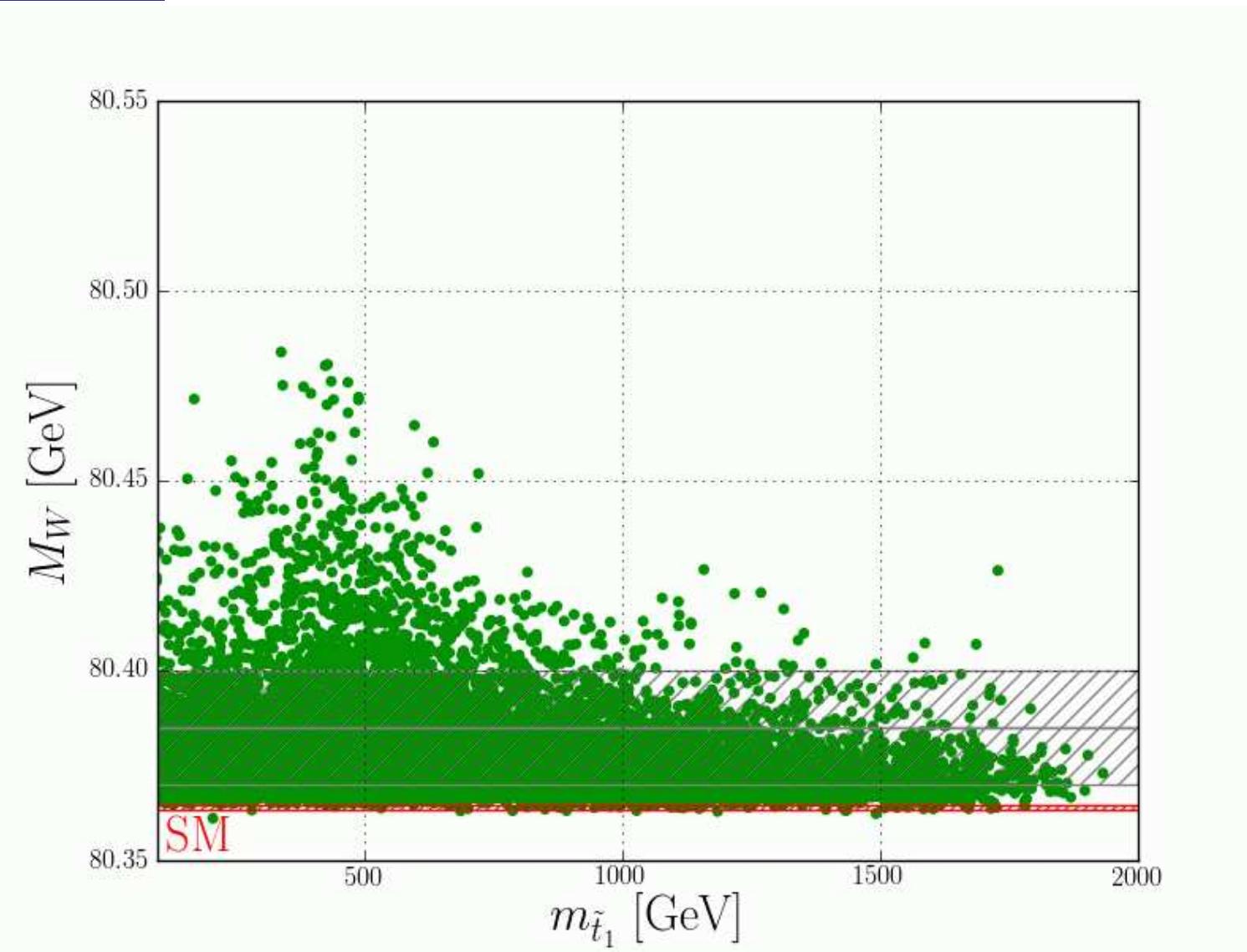




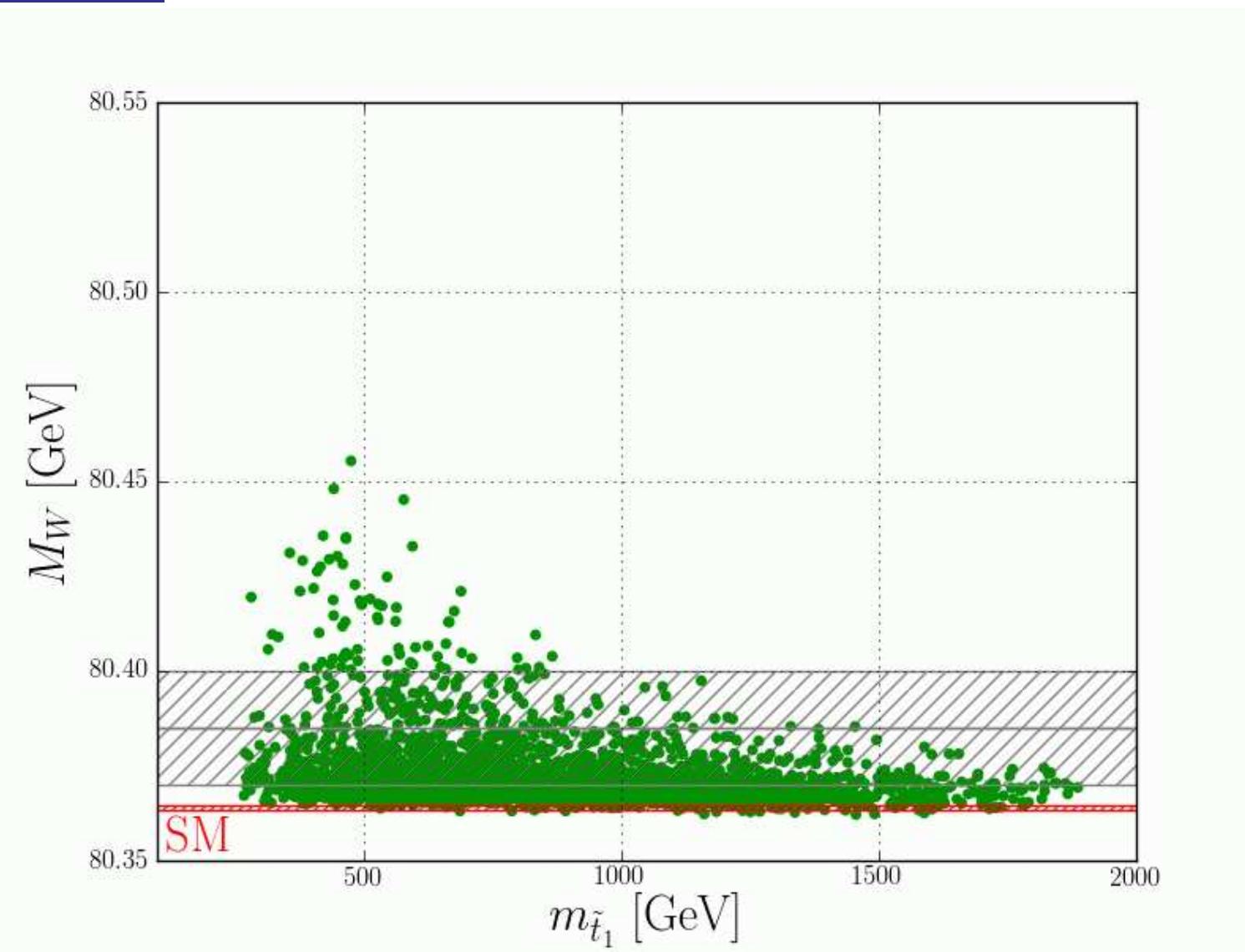
All points HiggsBounds allowed



$\dots \oplus m_{\tilde{q}_{1,2}}, m_{\tilde{g}} > 1200 \text{ GeV}$



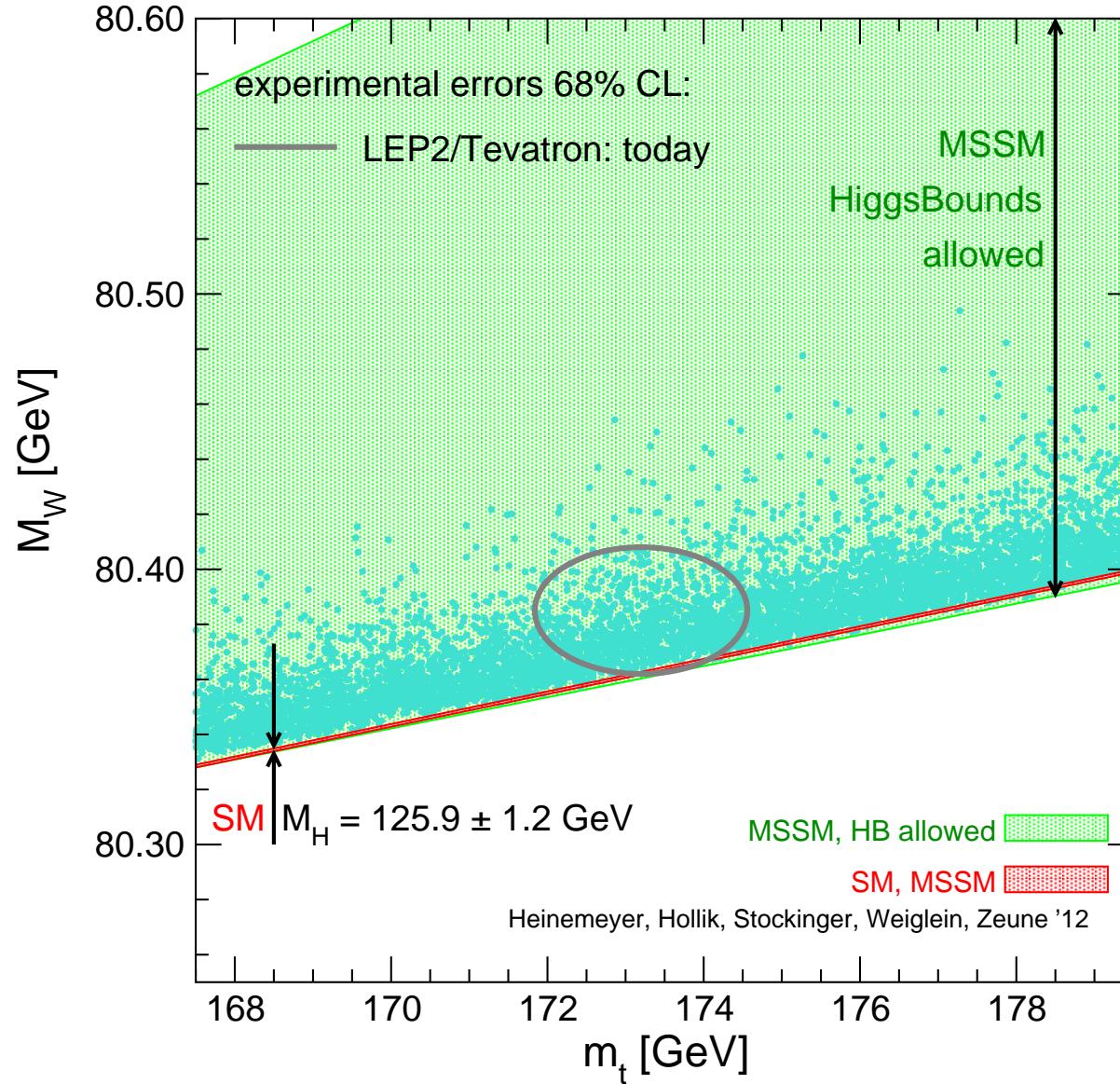
$\dots \oplus m_{\tilde{b}_i} > 500 \text{ GeV}$



$\dots \oplus m_{\tilde{l}}, m_{\tilde{\chi}_i^\pm}, m_{\tilde{\chi}_j^0} > 500 \text{ GeV}$ (but $\tilde{\chi}_1^0$ remains LSP)

Effects of stops, sbottoms, M_h :

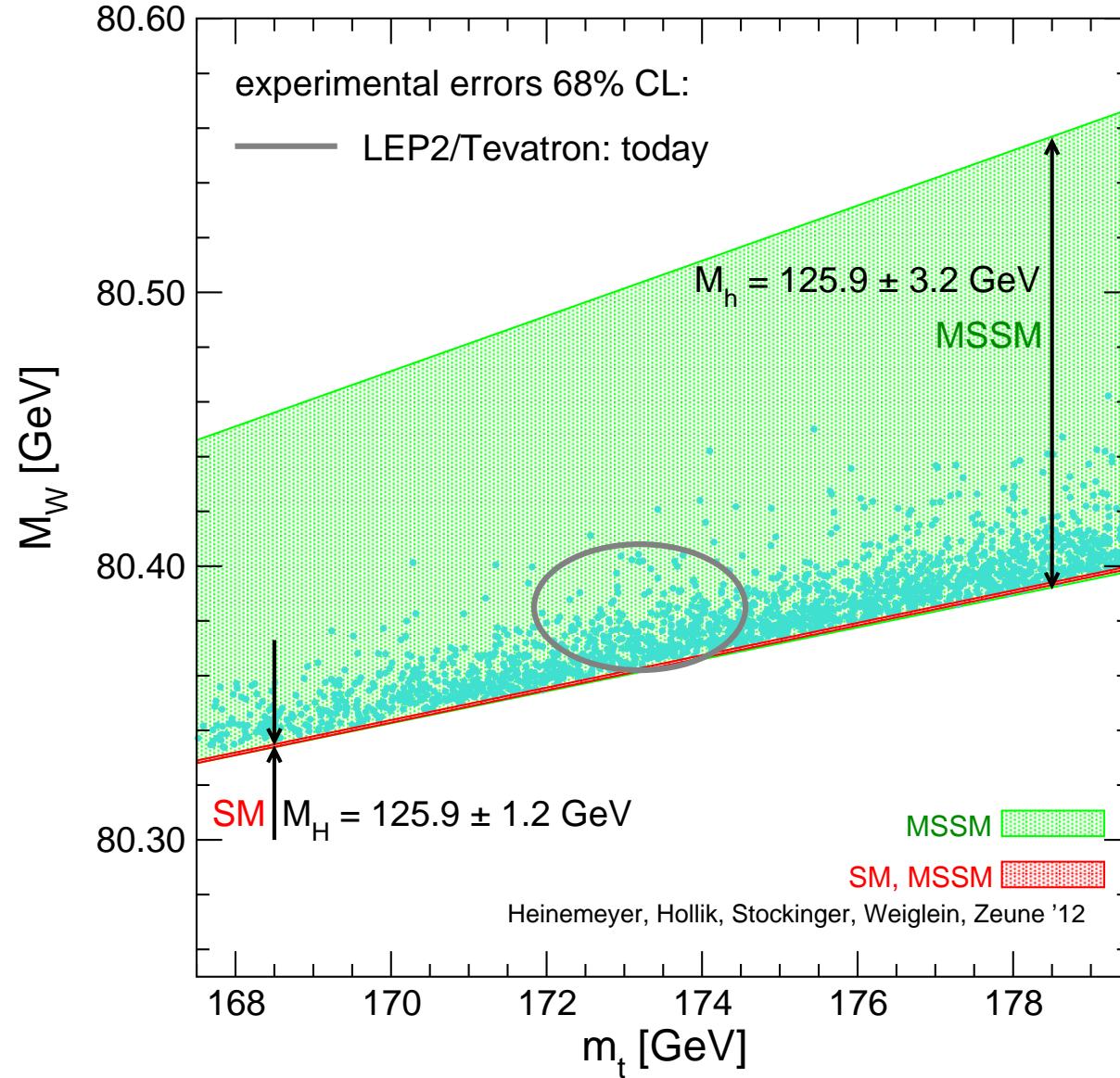
[S.H., G. Weiglein, L. Zeune '12 - PRELIMINARY]



light blue: $m_{\tilde{t}_i}, m_{\tilde{b}_j} > 500 \text{ GeV}, m_{\tilde{q}_{1,2}}, m_{\tilde{g}} > 1200 \text{ GeV}$

Effects of stops, sbottoms, M_h :

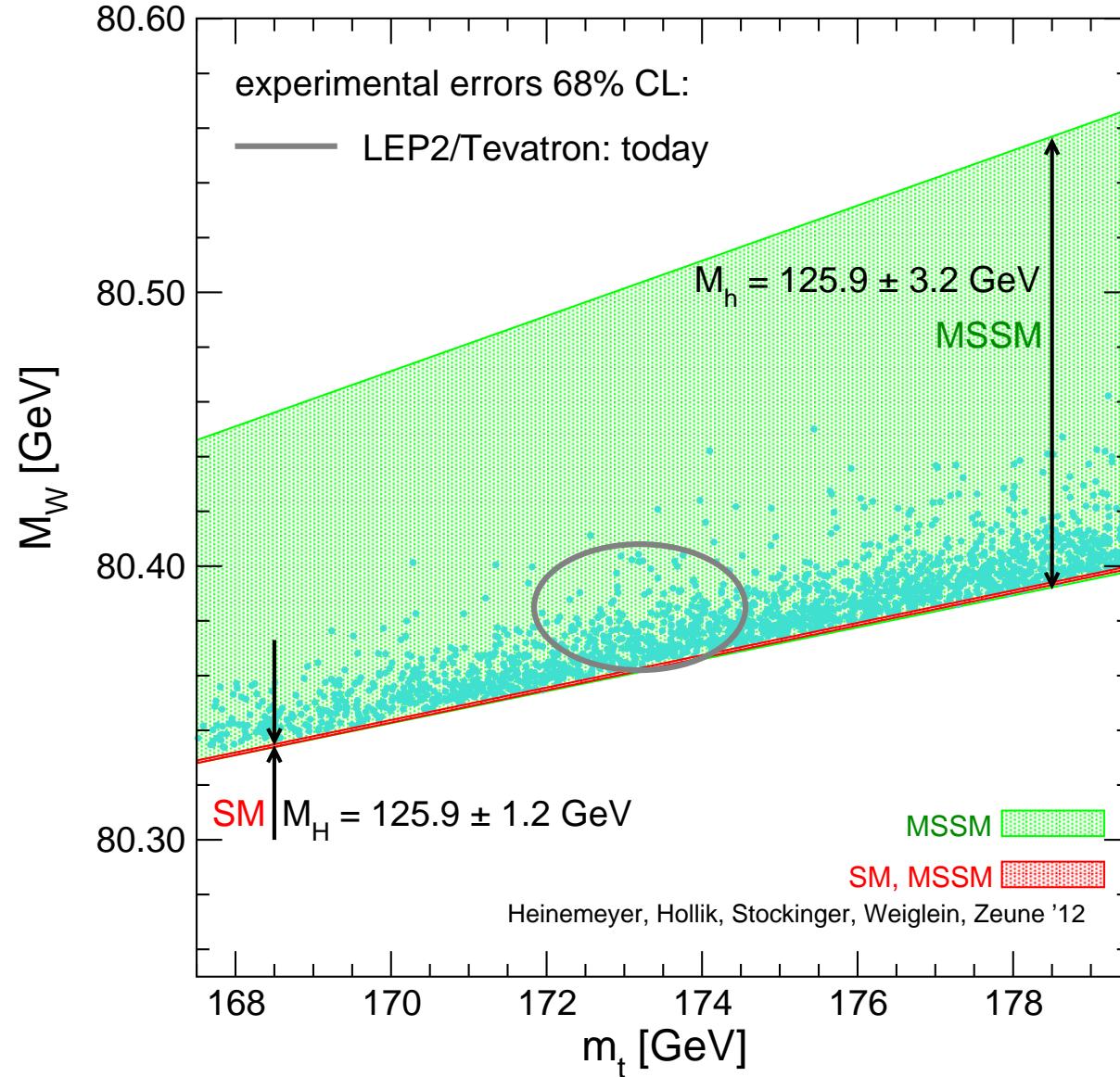
[S.H., G. Weiglein, L. Zeune '12 - PRELIMINARY]



light blue: $m_{\tilde{t}_i}, m_{\tilde{b}_j} > 500 \text{ GeV}$, $m_{\tilde{q}_{1,2}}, m_{\tilde{g}} > 1200 \text{ GeV}$

Effects of stops, sbottoms, M_h :

[S.H., G. Weiglein, L. Zeune '12 - PRELIMINARY]



⇒ light stop all over the place, no restrictions possible!

4. Conclusions

- EWPO can give valuable information about unknown parameters
- Main EWPO: M_W , $\sin^2 \theta_{\text{eff}}$, $(g - 2)_\mu$, M_h , ...
- Correct inclusion of uncertainties is crucial for reliable interpretations
 m_t gives largest uncertainties
- Fits so far only possible in GUT based models: CMSSM, NUHM1, ...
⇒ perfect fit for m_t and M_W
- $\sin^2 \theta_{\text{eff}}$: needs to be clarified with Gigaz
could find deviations beyond LHC
could rule out SM and/or MSSM
- MSSM parameter scan for M_W :
 - Effects of sleptons: $\gtrsim 70$ MeV
 - Effects of charginos: $\gtrsim 20$ MeV
 - $m_{\tilde{t}_1} \lesssim 1.5$ TeV can give “good” M_W

Back-up

GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

$$m_0, m_{1/2}, A_0, \tan\beta, \text{sign } \mu$$

m_0 : universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0 : universal trilinear coupling

$\tan\beta$: ratio of Higgs vacuum expectation values

$\text{sign}(\mu)$: sign of supersymmetric Higgs parameter

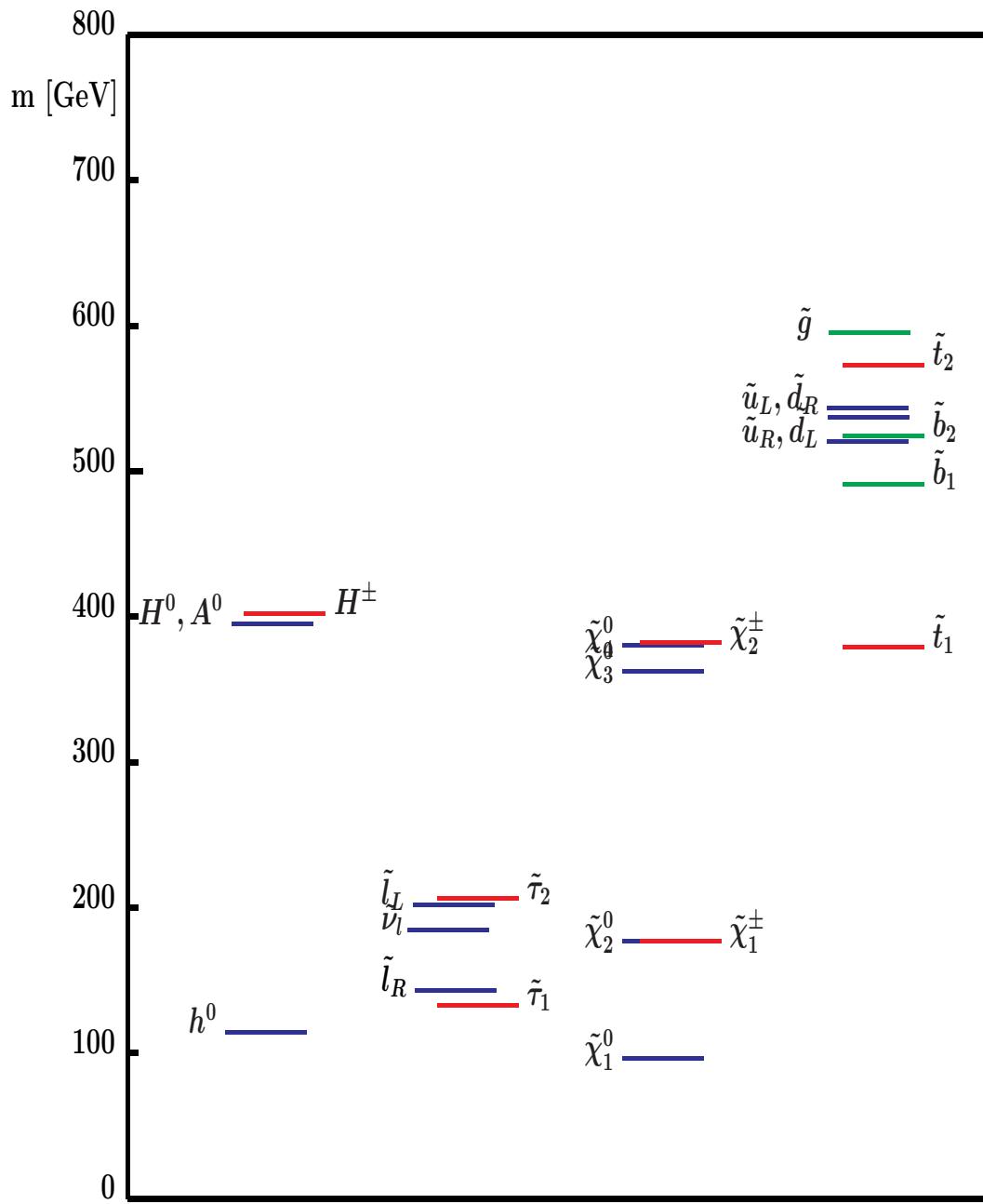
} at the GUT scale

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino

“Typical” CMSSM scenario
(SPS 1a benchmark scenario):

Strong connection between
all the sectors



GUT based models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of **scalar fermion** and **scalar Higgs** parameter at the GUT scale

⇒ effectively M_A or μ as free parameters at the EW scale

⇒ besides the CMSSM parameters

M_A or μ

And there is more: 3.) VCMSSM
4.) mSUGRA
5.) NUHM2

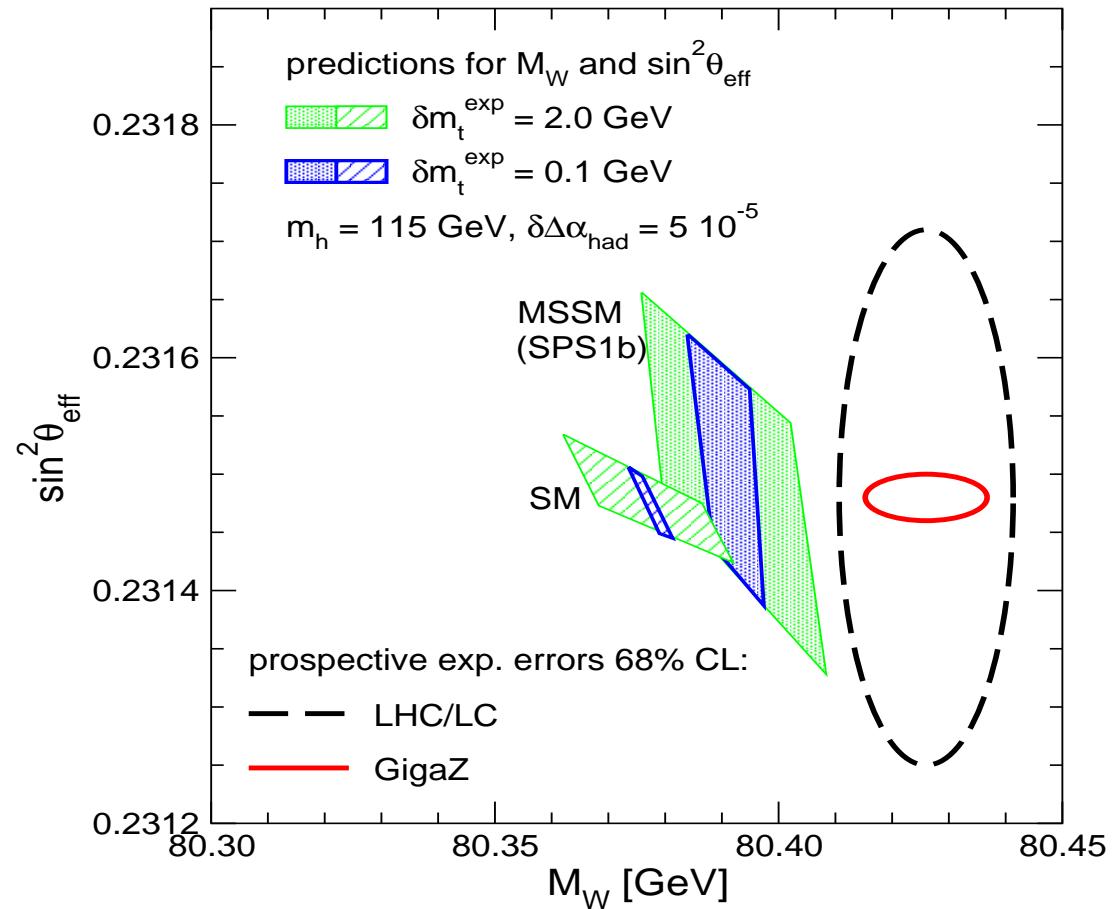
... no time here ...

Possible future scenario:

[S.H., S. Kraml, W. Porod, G. Weiglein '03]

SM: $M_H = 115$ GeV

MSSM: SPS 1b
all SUSY parameters varied
within realistic errors



$\delta m_t = 0.1$ GeV vs. $\delta m_t = 2$ GeV

⇒ SM: improvement by a factor ~ 10

⇒ MSSM: improvement by a factor $\sim 2 - 3$

Prediction of M_h in the CMSSM/NUHM1

[*O. Buchmüller, R. Cavanaugh, D. Colling, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, SH, G. Isidori, K. Olive, S. Rogerson, F. Ronga, G. Weiglein*]

General idea:

Take the most simple MSSM versions: **CMSSM/NUHM1**
→ just three/four GUT scale parameters + $\tan\beta$

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General idea:

Take the most simple MSSM versions: **CMSSM/NUHM1**
→ just three/four GUT scale parameters + $\tan\beta$

- combine **all electroweak precision data** as in the SM
- combine with **B physics observables**
- combine with **CDM** and $(g - 2)_\mu$
- include SM parameters with their errors: m_t, \dots
- scan over the **full CMSSM/NUHM1 parameter space**

Prediction of M_h in the CMSSM/NUHM1

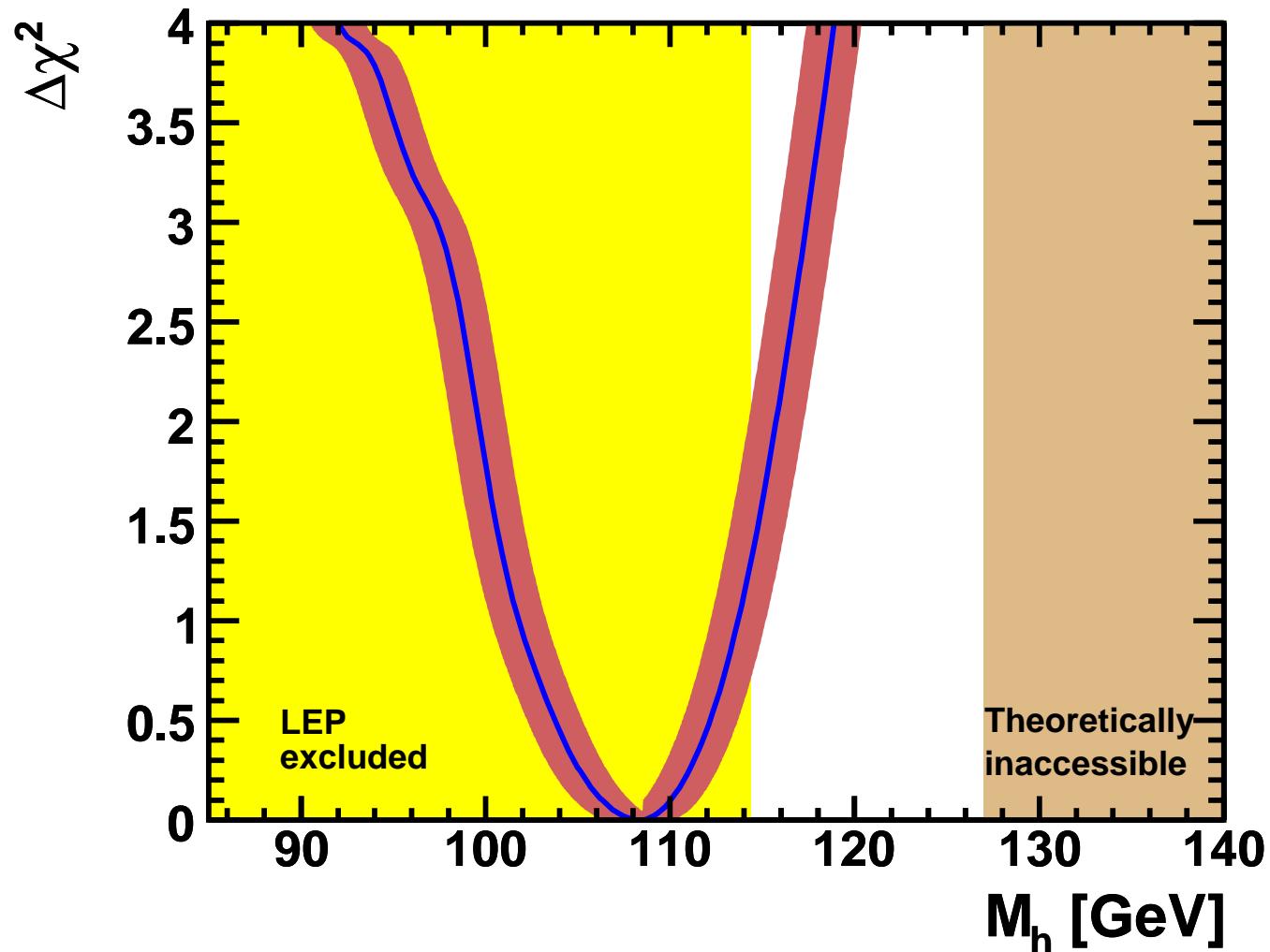
[*O. Buchmüller, R. Cavanaugh, D. Colling, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, SH, G. Isidori, K. Olive, S. Rogerson, F. Ronga, G. Weiglein*]

General idea:

Take the most simple MSSM versions: **CMSSM/NUHM1**
→ just three/four GUT scale parameters + $\tan\beta$

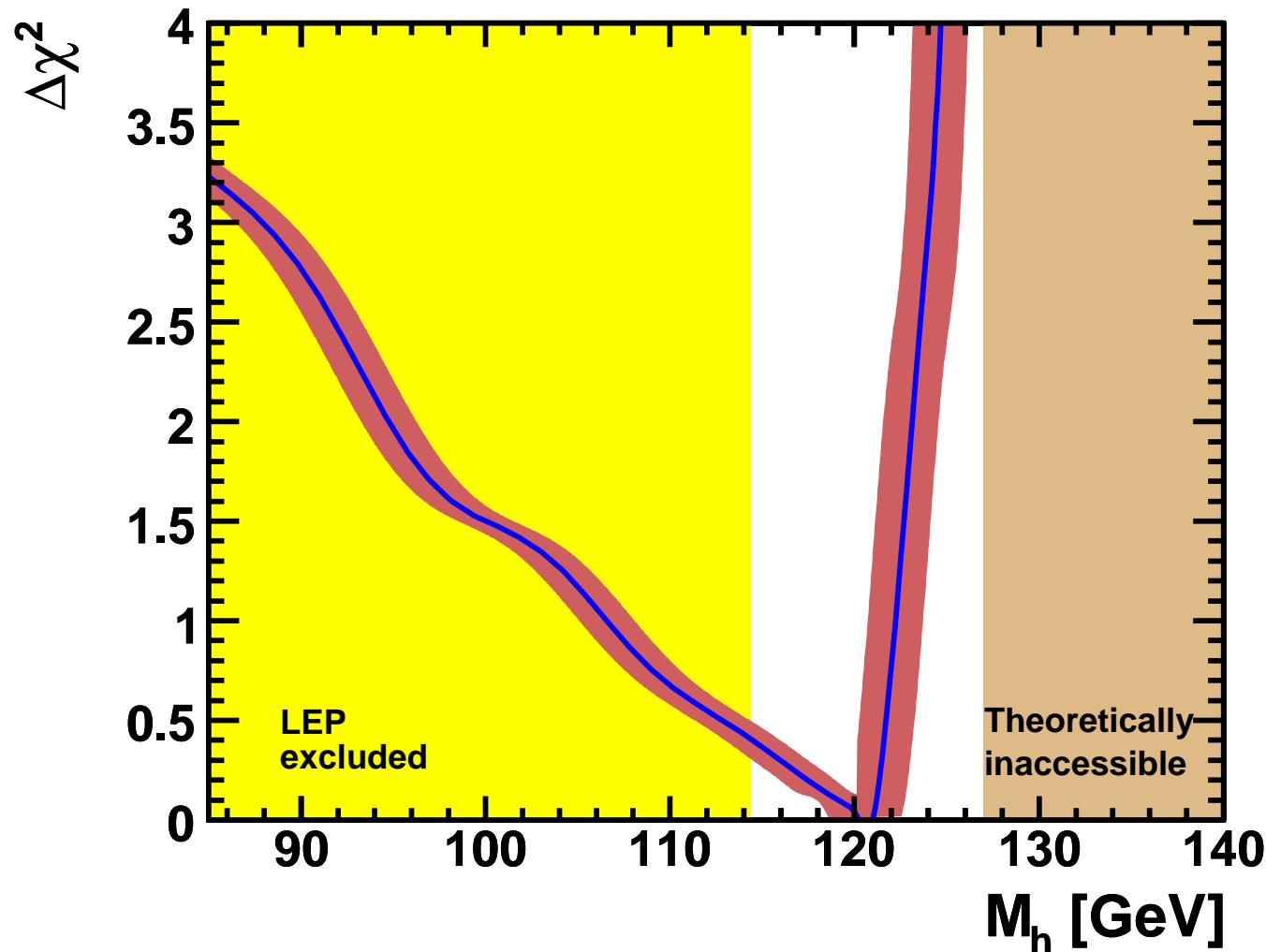
- combine all electroweak precision data as in the SM
- combine with **B** physics observables
- combine with **CDM** and $(g - 2)_\mu$
- include SM parameters with their errors: m_t, \dots
- scan over the full CMSSM/NUHM1 parameter space
⇒ preferred M_h values

CMSSM: red band plot (no LHC data):



$$M_h = 108 \pm 6 \text{ (exp)} \pm 1.5 \text{ (theo)} \text{ GeV}$$

NUHM1: red band plot (no LHC searches):

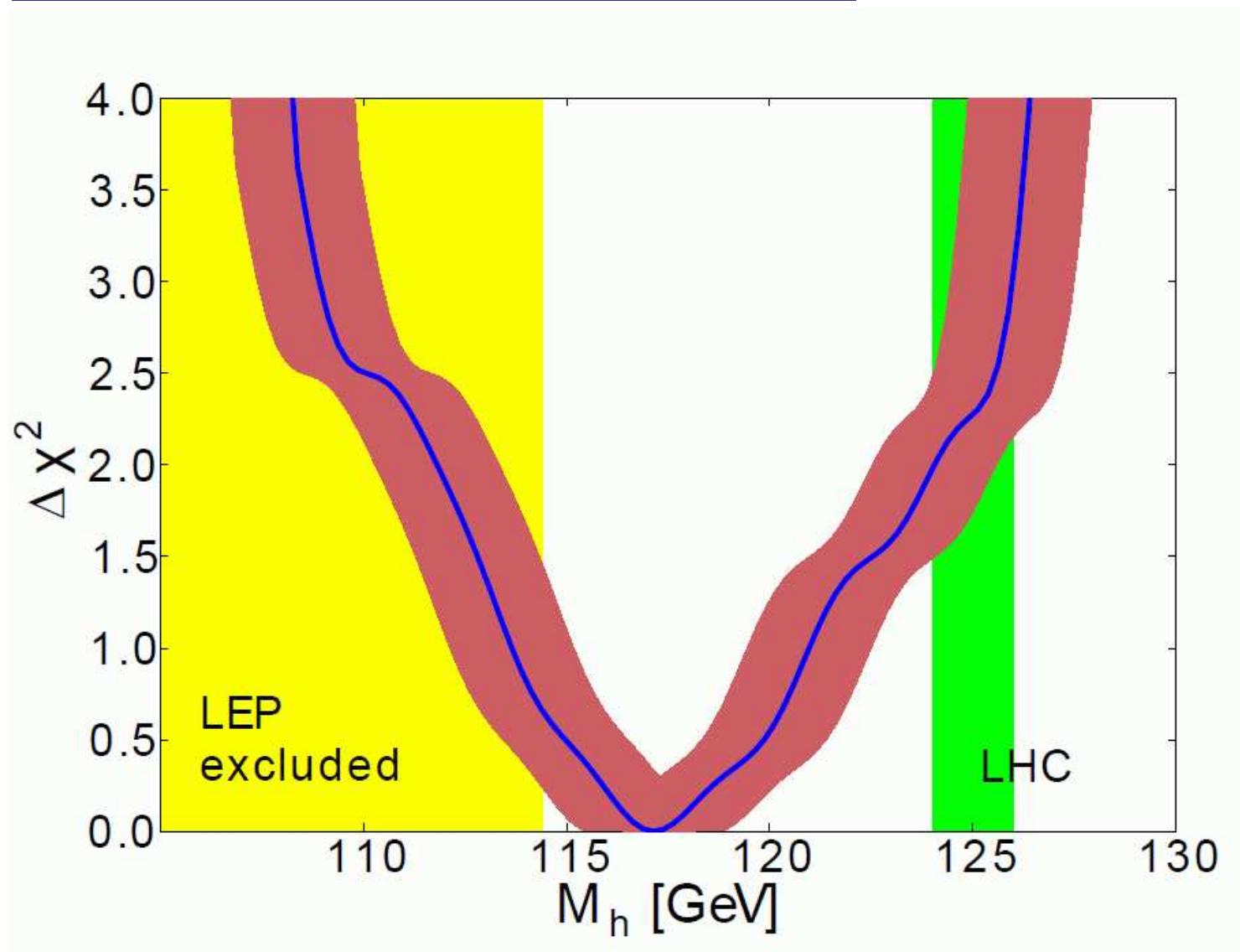


$$M_h = 121^{+1}_{-14} \text{ (exp)} \pm 1.5 \text{ (theo)} \text{ GeV}$$

⇒ naturally above LEP limit

CMSSM: post-LHC (5+5 fb^{-1}) red band plot:

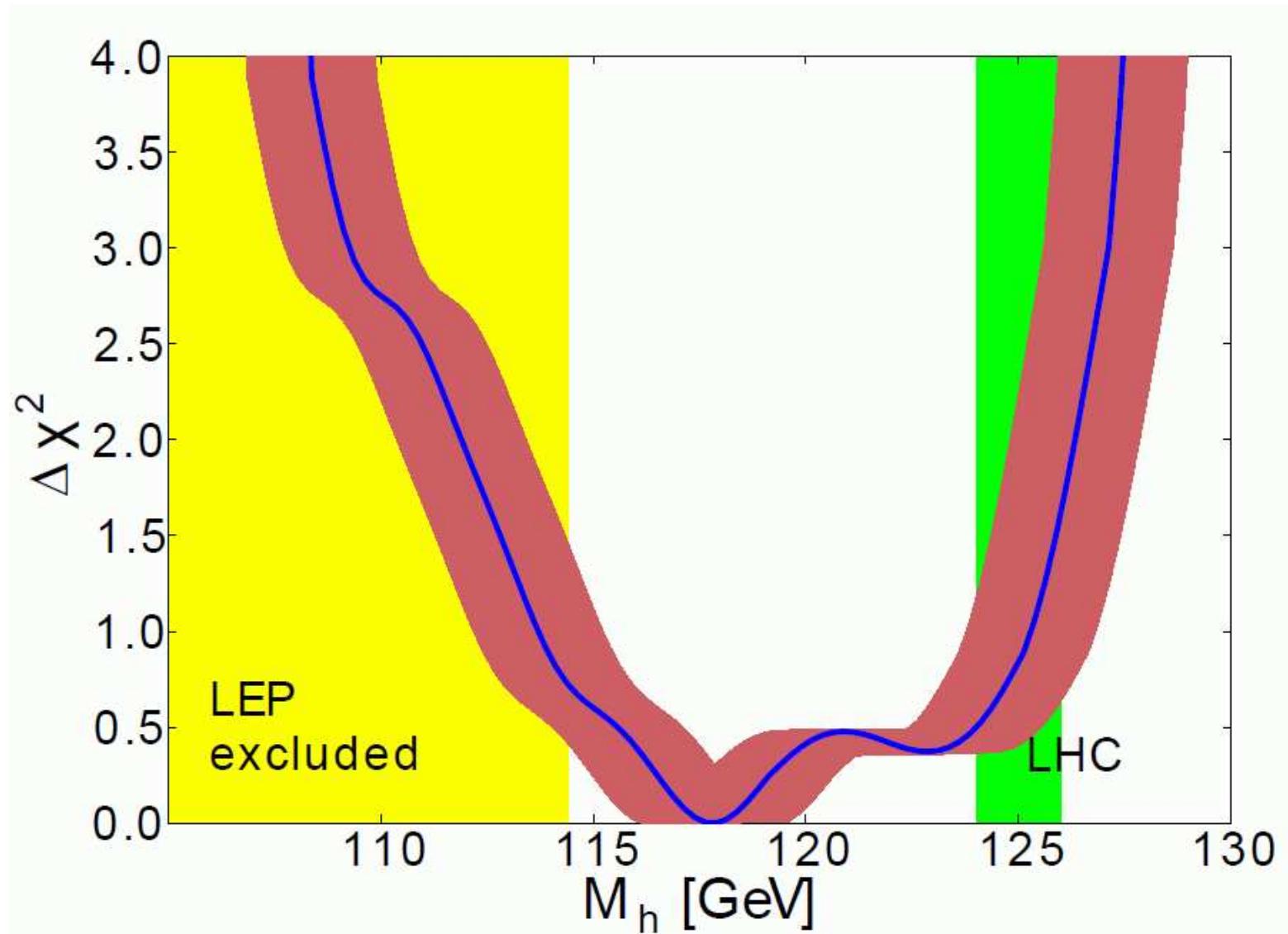
[2012]



$$M_h = 117 \pm 4 \text{ (exp)} \pm 1.5 \text{ (theo)} \text{ GeV} \quad \Delta\chi^2(M_h = 125 \text{ GeV}) \lesssim 2$$

NUHM1: post-LHC (5+5 fb^{-1}) red band plot:

[2012]



$$M_h \approx 118_{-4}^{+7} (\text{exp}) \pm 1.5 (\text{theo}) \text{ GeV} \quad \Delta\chi^2(M_h = 125 \text{ GeV}) \approx 0.5$$

Predictions for early LHC searches:

- combine all electroweak precision data as in the SM
- combine with B physics observables
- combine with CDM and $(g - 2)_\mu$
- include SM parameters with their errors: m_t , M_Z , $\Delta\alpha_{\text{had}}$

⇒ χ^2 function

→ scan over the full CMSSM/NUHM1/... parameter space
 $\sim 2.5 \cdot 10^7$ points samples with MCMC

statistical measure: χ^2 function (Frequentist, no priors)

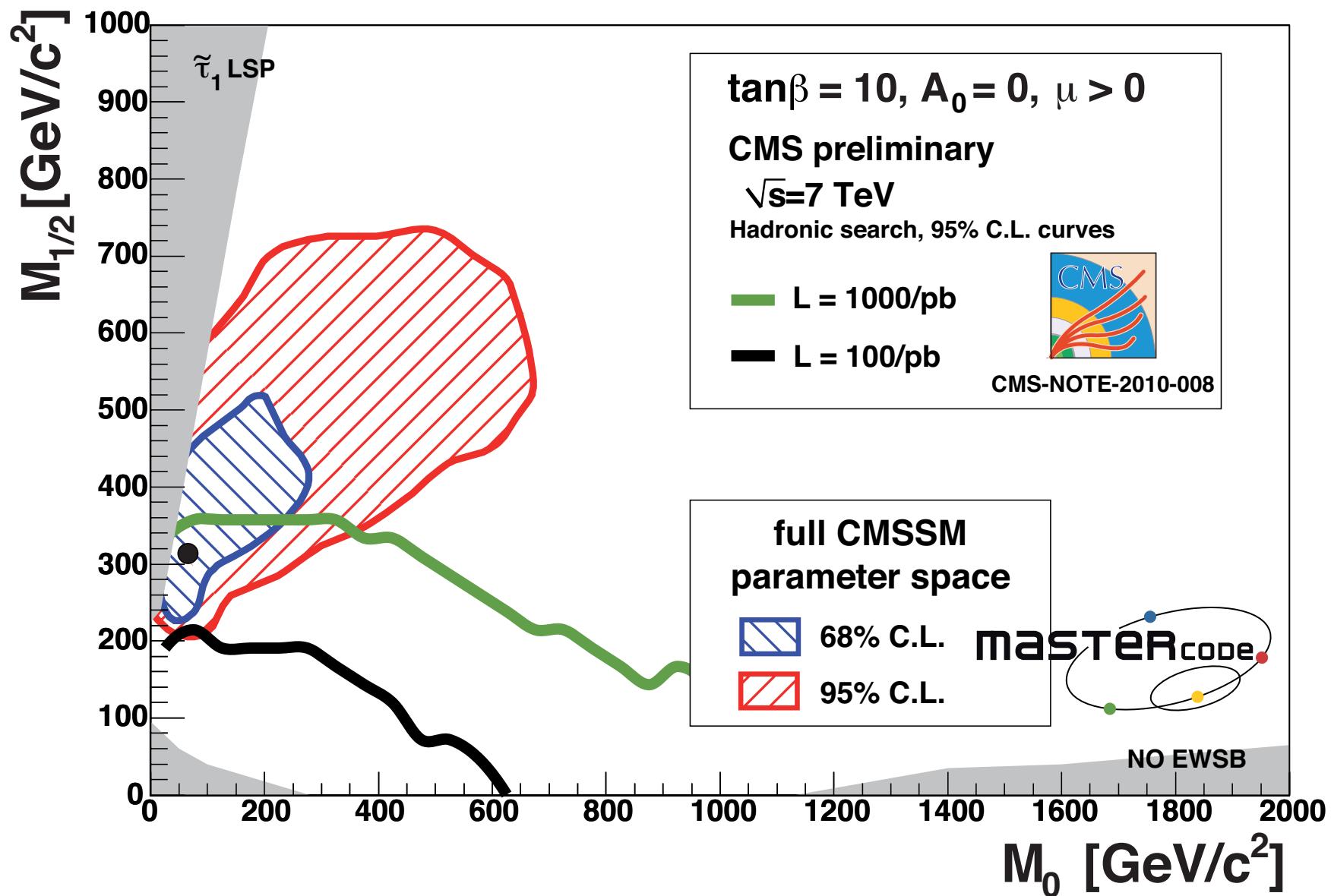
→ final minimum: Minuit

$\Delta\chi^2$: 68, 95% C.L. contours

⇒ preferred CMSSM/NUHM1/... parameters

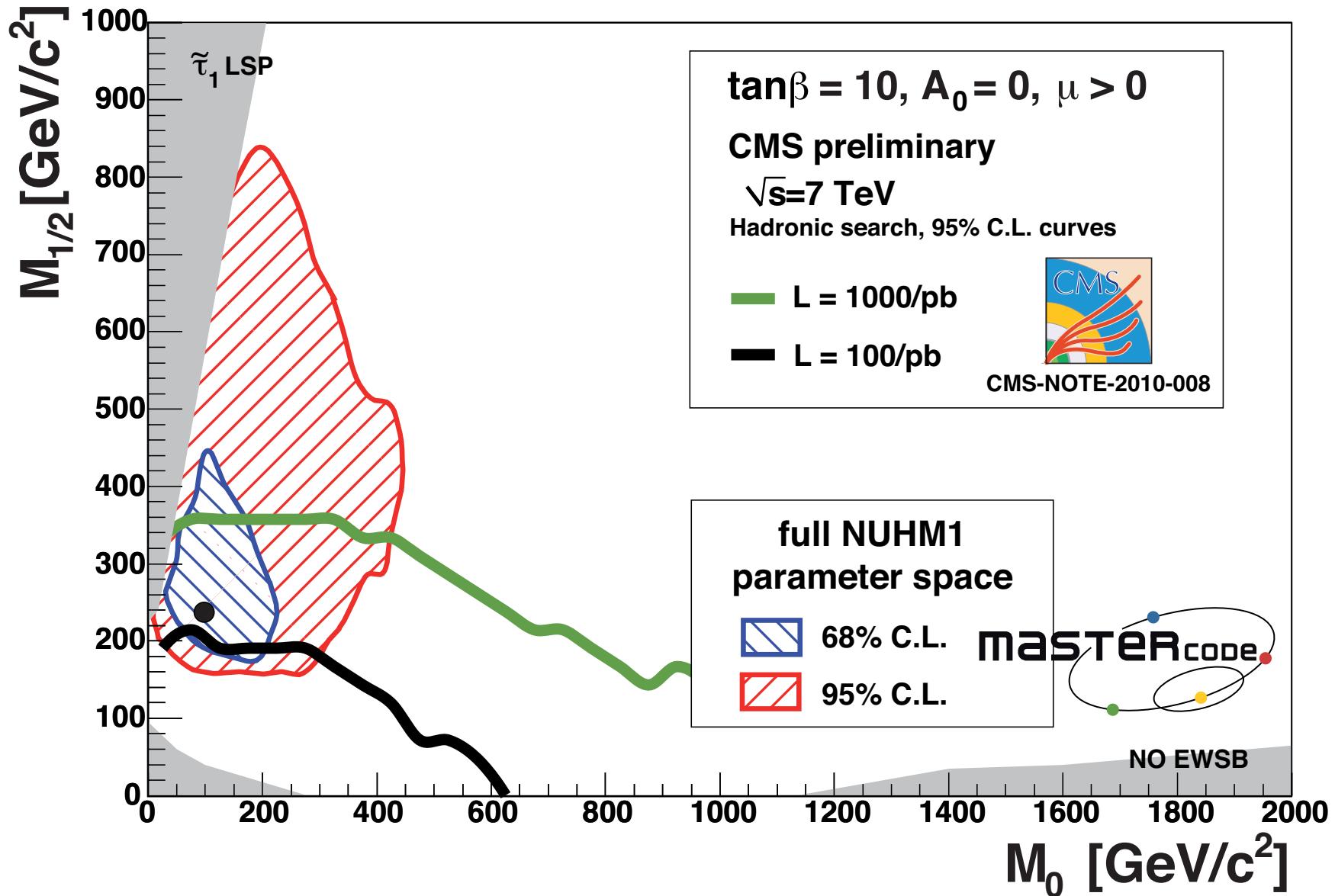
⇒ LHC (/ILC) reach

LHC (CMS) \oplus CMSSM analysis:



→ best-fit point and part of 68% C.L. are can be tested in 2011

LHC (CMS) \oplus NUHM1 analysis:



⇒ best-fit point and part of 68% C.L. are can be tested in 2011